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In the case of the blockage, however, because of small mass flow in the blocked region, the axial conduction is important and the present program must be used. Effects of variable or constant eddy diffusivity, wall boundary conditions, position of blockage and effective thermal conductivity of the solid are investigated.

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NUMERICAL STUDY OF FORMATION OF THERMAL NON UNIFORMITIES IN ACTIVE PACKED BEDS

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Abstract

The purpose of this work was to mathematically model the heat transfer in an active packed bed heat exchanger and to develope an appropriate numerical scheme for the solution of the temperature field. As active packed beds are being considered for use in nuclear reactors, concern is generated as to whether regions of relatively high temperatures will develope. Such concern is the impetus behind the application of our program to two applications concerning heat transfer in packed beds assuming (i) variable porosity of the Brosilow type and assuming (ii) the existence of blockages.

The results show that for the case of a packed bed with the porosity distribution the so-called hot spot occurrs near the wall of the bed. Its magnitude and position were seen to be strongly affected by the assumed velocity profile and wall boundary conditions. In addition as the proposed mathematical equations include axial conduction as opposed to a previously developed program which excluded axial conduction and as the results of the two programs approached one another as the Re increased, it is reasonable that the previous program, (as it is based on parabolic, not elliptic equations as in the present case), could be implimented with little error expected due to the lack of axial conduction.

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Nomenclature

Cp	($\frac{Btu}{lbm\text{-}°F}$)	specific heat capacity at constant pressure
Dp	(ft)	diameter of spherical particles of packed bed
E	(ft^2/ sec)	eddy diffusivity
h	(Btu/ft^2-hr-°F)	heat transfer coefficient between packed bed spheres and gas; based on unit area
h_v	(Btu/ft^3-hr-°F)	as above except it is based on unit volume
h_{sw}, h_{gw}	(Btu/ft^2-hr-°F)	heat transfer coefficients at the wall for the solid and gas
HT	(ft)	height of packed bed
ks, kg	(Btu/ft-hr-°F)	molecular thermal conductivities for the solid and gas
ks*, kg*	(Btu/ft-hr-°F)	effective thermal conductivities for the solid and gas
Nu	(Ø)	Nusselt number; $\frac{h \cdot Dp}{kg}$
Pe'	(Ø)	modified Peclet number; $\frac{V_o \cdot Dp}{E}$
Pr	(Ø)	Prandtl number; $\frac{\mu \cdot Cp}{kg}$
Q'	(Btu/ft^3)	rate of heat production per unit solid volume
r	(ft)	position in radial direction
r*	(Ø)	non-dimensionalized radial position; r/RT
RT	(ft)	radius of packed bed
Re	(Ø)	Reynolds number; $\frac{V_o \cdot RT}{\nu}$
Ts, Tg	(°F)	temperature of solid and gas
T	(Ø)	non-dimensionalized gas temperature; Tg/T_o
Ta	(°F)	ambient, wall temperature
T_o	(°F)	inlet gas temperature
V	(ft/sec)	axial velocity

U^*	(ϕ)	non-dimensional axial velocity; U/V_o
V	(ft/sec)	radial velocity
V^*	(ϕ)	non-dimensional radial velocity; V/V_o
V_o	(ft/sec)	mean inlet gas velocity
x	(ft)	longitudinal position
x^*	(ϕ)	non-dimensional longitudinal position; x/HT
ϵ	(ϕ)	porosity; $\frac{(\text{ voidage volume })}{(\text{ unit volume })}$
ρ	(lbm/ft^3)	density of the flowing medium
θ	(ϕ)	non-dimensional temperature of the solid
τ	($lbm/ft\text{-}sec^2$)	viscous stresses
μ	(lbm/ft-sec)	dynamic viscosity
ν	(ft^2/sec)	kinematic viscosity;

1. Introduction

Heat exchangers have diversified uses in industry. The transfer of heat to a flowing meduium; the storage of heat; and chemical regeneration are a few such uses. More specifically, packed bed heat exchangers offer the advantage that large rates of heat/chemical transfer can take place in a relatively small volume. A packed bed is typically a collection of small spheres, (however various shapes are possible), housed in a cylindrical tube in such a manner that the spheres' positions are stationary; see figure 1. Small, tightly packed particles are what yield the high surface to volume ratio, $6\cdot(1-\epsilon)/Dp$; thereby resulting in good heat transfer properties. Such an advantage is why packed beds, with elements coated with fissionable material; were considered as likely candidates for use as nuclear reactor cores. In fact, plants using such packed beds as reactor cores, are in operation presently.

One concern, however, with the application of packed beds in nuclear reactors, is the existence of regions where temperatures can achieve significantly higher levels than the rest of the field. Such concern stems from the fear that greater-than-disigned-for temperatures can arrise in these regions and may impare the safe operation of the facility. These regions of relatively high temperatures arrise from two principle causes: (i) because of the nonuniformity of the porosity distribution, ϵ, regions of relative minima in ϵ develope where relatively large heat transfer rates occurr between solid and gas, (thereby resulting in higher temperatures), and (ii) because of blockages that may develope as a result of a) the retention of dust or foreign matter or b) of the breakage of particles due to possible thermal stresses, higher temperatures may result as well.

It would therefore be useful to be able to mathematically model the problem of heat transfer in a bed of active particles where variations in the porosity occurr or blockages exist, and subsequently develope a numerical technique for distributions. Such is the purpose of this work.

The paper will be divided into six chapters: the mathematical statement of heat exchange in an active packed bed; numerical approach used for the solution; optimization and verification of numerical approach; study of the formation of hot spots due to variations in the porosity distribution; study of formation of hot spots due to blockages; and summary of

important results and conclusions.

1. Mathematical Statement of the Problem

The first choice that must be made in modeling heat transfer in a packed bed is whether to enforce the conservation of energy by considering the gas/solid mixture or by considering the gas and solid separately; i.e., to consider a one phase or two phase system. A two phase approach is chosen for this work. In addition, as variations in the θ direction are assumed to be zero, an axis-symmetric, two-dimensional system is used.

The pair of differential equations, conserving energy in the gas and solid state respectively, are derived in appendix A. The results are:

conservation of energy in the gas:

$$(1.)\ (\rho U Cp)\frac{\partial Tg}{\partial x} + (\rho V Cp)\frac{\partial Tg}{\partial r} - \frac{\partial}{\partial x}\left(kg^{*}\cdot\frac{\partial Tg}{\partial x}\right) - \frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r kg^{*}\cdot\frac{\partial Tg}{\partial r}\right) = h_v\cdot(Ts - Tg)$$

conservation of energy in the solid:

$$(2.)\ -\frac{\partial}{\partial x}\left(ks^{*}\cdot\frac{\partial Ts}{\partial x}\right) - \frac{1}{r}\ \frac{\partial}{\partial r}\left(r\cdot ks^{*}\cdot\frac{\partial Ts}{\partial r}\right) = h_v\cdot(Tg - Ts) + Q'\cdot(1-\epsilon)$$

The basic assumptions are enumerated in appendix A. ks* and kg* are effective thermal conductivities. It is left to express these quantities in terms of their molecular counterparts ks and kg. kg* is given as in reference (1): $kg^{*} = \epsilon\cdot kg + \rho\cdot Cp\cdot E$. This form is identical, save for the factor ϵ, to what the effective thermal conductivity becomes when one assumes an eddy diffusivity, associated with the Reynolds stresses in the averaged turbulent momentum equation, that is defined analogously as is defined for the viscous stresses τ in the Navier-Stokes equations.

kg* has an additional term, $\rho\cdot Cp\cdot E$, which takes account of the heat dissipated by the turbulent flucuations. We take ks* as: $ks^{*} = (1-\epsilon)\cdot ks$. However, this form for ks* only takes account of the gross effect that porosity may have on the effective thermal conductivity. It fails to consider that heat conducted through the solid phase really depends upon the number of contact points between spheres in a given region. Given that conductivity based on the number of contact points is hard to define, we use the above-mentioned expression for ks*. It is important to notice that these expressions for kg* and ks* take account of the fact that not all of the surface of any given face of V (the differential volume in appendix A.), is entirely available to either

the conductive energy flux of the gas phase or of the solid phase. This is expressed by the terms $\epsilon \cdot kg$ and $(1 - \epsilon) \cdot ks$.

In the construction of the differential equqtions, we make the assumption that the porosity "at a point", based on an infinitessimal volume element, is the same as what would be given if the porosity were based on any planar side of the infinitessimal volume element; i.e., at a given point, ϵ based on volume, is equal to ϵ based on area. However talking about porosity defined at a point is rather misleading; for, given a point at r,θ,x, strictly speaking the porosity is either zero or one. Therefore the porosity is discontinuous and the application of partial differential equations is invalid. But, as our partial differential equations do not incorporate variations in the θ direction, we may, hypothetically anyway, average out the variations of ϵ in the θ direction. Assuming such a function could be experimentally derived, this yields a continuous function in x and r. See figure 2. for a clarifying illustration. A function in r that we use in much of our calculations is as given in reference (3):

$$(3.)\ \epsilon = 0.4 + 0.3\ \mathrm{Exp}\ (-3.5\ (\frac{RT}{Dp}\ (1 - \frac{r}{RT})) + \cos\ (6.28\ (\frac{RT}{Dp}\ (1 - \frac{r}{RT}))) \cdot \mathrm{Exp}\ (-0.8\ (\frac{RT}{Dp}\ (1 - \frac{r}{RT})))$$

Equations (1.) and (2.) form a coupled elliptic system for the unknown temperatures Tg and Ts. Therefore Diriclet, Neumann and/or mixed boundary conditions must be specified for both the solid and gaseous temperatures, completely around the boundary. The boundaty conditions used are:

$$(4.)\quad \begin{aligned} &(x = 0,\ r):\ Tg = To;\ \frac{\partial Ts}{\partial x} = 0,\ \text{or}\ Ts = To \\ &(x,\ r = RT):\ -kg^* \frac{\partial Tg}{\partial r} = h_{gw} \cdot (Tg - Ta);\ -ks^* \frac{\partial Ts}{\partial r} = h_{sw} \cdot (Ts - Ta) \\ &(x = HT,\ r):\ \frac{\partial Tg}{\partial x} = \frac{\partial Ts}{\partial x} = 0 \\ &(x,\ r = 0):\ \frac{\partial Tg}{\partial r} = \frac{\partial Ts}{\partial r} = 0 \end{aligned}$$

In passing, the other parameters used in (1.) and (2.) include h_v, the volumetric heat transfer coefficient which governs the rate of heat transfer between solid and gas, and Q' the rate of heat production per unit solid volume.

The boundary conditions at the inlet reflect (i) that the gas enters at a known temperature and (ii) that the solid could also maintain this temperature or could assume, as the gas and solid temperature fields do

at the exit, what we believe the more realistic condition that the normal derivative of the temperature is zero. The boundary conditions at the longitudinal axis simply reflect an assumed symmetry property. The boundary condition at the wall is a mixed one. Setting h_{gw}/kg^* and h_{sw}/ks^* equal to zero or a very large number, an adiabatic or an isothermal wall condition, respectively, is enforced.

2. Numerical Treatment of the Problem

In preparing (1.) , (2.) and (4.) for numerical treatment, it is conenient to non-dimensionalize them beforehand. Using the expressions:

$$x^* = x/HT,\ r^* = r/RT,\ U^* = U/Vo,\ V^* = V/Vo,\ T = Tg/To,\ \theta = Ts/To,$$
$$Pr = \mu Cp/kg,\ Re = Vo\cdot RT/\nu,\ Nu = h\cdot Dp/kg,\ ks^* = (1-\epsilon)\cdot ks,$$
$$kg^* = \epsilon\cdot kg + \rho\cdot Cp\cdot E$$

we get the following non-dimensional equations and boundary conditions:

(5.)
$$\frac{-1}{Re\cdot Pr}\cdot\frac{RT}{HT^2}\cdot(\epsilon + Pr\cdot(E/\nu))\frac{\partial^2 T}{\partial x^{*2}} - \frac{-1}{Re\cdot Pr}\cdot\frac{RT}{RT^2}\cdot(\epsilon + Pr\cdot(E/\nu))\frac{\partial^2 T}{\partial r^{*2}} +$$
$$\left(\frac{U^*}{HT} - \frac{-1}{Re\cdot Pr}\cdot\frac{RT}{HT^2}\cdot\left(\frac{\partial\epsilon}{\partial x^*} + Pr\cdot\frac{\partial}{\partial x^*}(E/\nu)\right)\right)\frac{\partial T}{\partial x^*} +$$
$$\left(\frac{V^*}{RT} - \frac{-1}{Re\cdot Pr}\cdot\frac{RT}{RT^2}\cdot\left(\frac{\partial\epsilon}{\partial r^*} + Pr\cdot\frac{\partial}{\partial r^*}(E/\nu)\right) - \frac{1}{r^*}\cdot\frac{(\epsilon + Pr\cdot(E/\nu))\cdot RT}{Re\cdot Pr\cdot RT^2}\right)\frac{\partial T}{\partial r^*} =$$
$$\frac{6\cdot(1-\epsilon)\ Nu}{Re\cdot Pr}\cdot\frac{RT}{Dp^2}\cdot(\theta - T)$$

(6.)
$$\frac{-RT}{HT^2}\cdot\frac{(1-\epsilon)}{Re\cdot Pr}\cdot(ks/kg)\frac{\partial^2\theta}{\partial x^{*2}} - \frac{RT}{RT^2}\cdot\frac{(1-\epsilon)}{Re\cdot Pr}\cdot(ks/kg)\frac{\partial^2\theta}{\partial r^{*2}} +$$
$$\frac{RT}{HT^2\cdot Re\cdot Pr}\cdot\left((ks/kg)\frac{\partial\epsilon}{\partial x^*} - (1-\epsilon)\cdot\frac{\partial(ks/kg)}{\partial x^*}\right)\frac{\partial\theta}{\partial x^*} +$$
$$\frac{RT}{RT^2\cdot Re\cdot Pr}\cdot\left(\left(\frac{\partial\epsilon}{\partial r^*} - \frac{(1-\epsilon)}{r^*}\right)(ks/kg) - (1-\epsilon)\frac{\partial(ks/kg)}{\partial r^*}\right)\frac{\partial\theta}{\partial r^*} =$$
$$\frac{6\cdot(1-\epsilon)}{Dp^2}\cdot Nu\cdot\frac{RT}{Re\cdot Pr}\cdot(T-\theta) + \frac{RT\cdot Q'\cdot(1-\epsilon)}{Re\cdot Pr\cdot kg\cdot To}$$

(7.)
$$(x^* = 0,\ r^*):\ T = 1,\ \frac{\partial\theta}{\partial x^*} = 0 \text{ or } \theta = 1$$
$$(x^*,\ r^* = 1):\ -\frac{\partial T}{\partial r^*} = (h_{gw}\cdot RT/kg^*)\cdot(T - Ta/To)$$
$$-\frac{\partial\theta}{\partial r^*} = (h_{sw}\cdot RT/ks^*)\cdot(\theta - Ta/To)$$
$$(x^* = 1,\ r^*):\ \frac{\partial T}{\partial x^*} = \frac{\partial\theta}{\partial x^*} = 0$$
$$(x^*,\ r^* = 0):\ \frac{\partial T}{\partial r^*} = \frac{\partial\theta}{\partial r^*} = 0$$

Such a system of equations and boundary conditions must in general be solved numerically. A constant space grid that is used is indexed below:

Writing (5.) and (6.) symbolically as

$$-AA1\frac{\partial^2 T}{\partial x^{*2}} - CC1\frac{\partial^2 T}{\partial r^{*2}} + U1\frac{\partial T}{\partial x^*} + V1\frac{\partial T}{\partial r^*} + H\cdot T = H\cdot\theta$$

$$-AA2\frac{\partial^2 \theta}{\partial x^{*2}} - CC2\frac{\partial^2 \theta}{\partial r^{*2}} + U2\frac{\partial \theta}{\partial x^*} + V2\frac{\partial \theta}{\partial r^*} + H\cdot\theta = H\cdot T + Q$$

and given the finite difference expressions,

$$\left(\frac{\partial^2 T}{\partial r^{*2}}\right)_{ij} = (T_{ij+1} - 2\,T_{ij} + T_{ij-1})/DR^2$$

$$\left(\frac{\partial^2 T}{\partial x^{*2}}\right)_{ij} = (T_{i+1j} - 2\,T_{ij} + T_{i-1j})/DX^2$$

$$\left(\frac{\partial T}{\partial x^*}\right)_{ij} = (T_{ij} - T_{i-1j})/DX$$

$\left(\frac{\partial T}{\partial r^*}\right)_{ij} = (T_{ij+1} - T_{ij-1})/2\cdot DR$, simimarily for θ, one can derive the following difference equations for T and θ:

$$(8.)\quad T_{ij-1}\left(\frac{-CC1}{DR^2} - \frac{V1}{2\cdot DR}\right) + T_{ij}\left(2\left(\frac{AA1}{DX^2} + \frac{CC1}{DR^2}\right) + \frac{U1}{DX} + H\right) + T_{ij+1}\left(\frac{-CC1}{DR^2} + \frac{V1}{2\cdot DR}\right) - \theta_{ij}\,(H) = T_{i-1j}\left(\frac{AA1}{DX^2} + \frac{U1}{DX}\right) + T_{i+1j}\left(\frac{AA1}{DX^2}\right)$$

$$(9.)\quad \theta_{ij-1}\left(\frac{-CC2}{DR^2} - \frac{V2}{2\cdot DR}\right) + \theta_{ij}\left(2\left(\frac{AA2}{DX^2} + \frac{CC2}{DR^2}\right) + \frac{U2}{DX} + H\right) + \theta_{ij+1}\left(\frac{-CC2}{DR^2} + \frac{V2}{2\cdot DR}\right) - T_{ij}\,(H) = \theta_{i-1j}\left(\frac{AA2}{DX^2} + \frac{U2}{DX}\right) + \theta_{i+1j}\left(\frac{AA2}{DX^2}\right) + Q_{ij}$$

One could consider, in the solution of (8.) and (9.), that temperatures at all nodal points are unknown values. But as this would lead to the inversion of an extremely large, sparse matrix, an alternate method should be found. The problem in employing any alternate scheme is the existence of the terms in (8.) and (9.) contributed by the axial conduction; namely T_{i+1j} and θ_{i+1j} . If the temperatures along row i are to be solved for, then guessed values must be assumed for these terms. An iterative procedure is clearly called for. This is the complication introduced by the elliptic nature of the equations.

Assuming that all temperatures are known in the $k^{\underline{th}}$ iteration at all grid points up to and including the $(i-1)^{\underline{st}}$ row and in the $(k-1)^{\underline{st}}$ iteration in the $i^{\underline{th}}$ row and above, the coupled differenced equations (8.) and (9.) are applied to the temperatures in the $i^{\underline{th}}$ row of grid points for all j. A special type of matrix equation is obtained whose form is shown in figure 3. Employing an efficient subroutine to solve this matrix system for T_{ij} and θ_{ij} along row i, these values are subsequently "over-relaxed" by the use of a method which employs the

following formulas:

$$(T_{ij})_k = (T_{ij})_{k-1} + WS\cdot((T_{ij})_{matrix} - (T_{ij})_{k-1})$$
$$(\theta_{ij})_k = (\theta_{ij})_{k-1} + WS\cdot((\theta_{ij})_{matrix} - (\theta_{ij})_{k-1})$$

This procedure is termed relaxation by lines and is used to accelerate the convergence of the solution method. WS is called the over-relaxation factor, whose value is typically between 1 and 2. As we proceed to the next row, we can use the newly updated values of the $i^{\underline{th}}$ row in our calculation of the values in the $(i+1)^{st}$ row as given by the matrix equation. Proceeding in this manner through the bed one can check whether the largest error between iterations satisfies some error criterion. If not, one must start the process again, repeating as many iterations as necessary so as to obtain convergence.

As a final note, it may have been observed that the finite difference expressions used for $\frac{\partial T}{\partial x}$ in deriving (3.) was a first order, one-sided difference expression; unlike the central difference equation for $\frac{\partial T}{\partial r}$. The reasoning for this lies in the assertion that for high enough Re the first derivative term in equations (5.) is significantly greater in magnitude than other terms, and, according to reference (4), to avoid numerical instabilities in the solution as well as enhance the accurracy of the solution, the one-sided, or upwind, differencing scheme should be employed to $\frac{\partial T}{\partial x}$. Unfortunately the upwind differencing scheme was also applied to $\frac{\partial \theta}{\partial x}$. As no relative weighting with respect to Re exists between the first and second derivative terms in equation (2.), the rational for using the upwind scheme for $\frac{\partial T}{\partial x}$ was inappropriate for use on $\frac{\partial \theta}{\partial x}$. Therefore it was inconsistent to apply upwind differencing to $\frac{\partial \theta}{\partial x}$ and it is possible that the solutions obtained were not as accurrate as could have been obtained using central differencing on $\frac{\partial \theta}{\partial x}$; however the discrepencywould be small and would have no implications on conclusions to be drawn.

3. Optimization and Verification of Numerical Method

This chapter concerns itself with the actual implimentation of the numerical method in obtaining solutions with the purpose of minimizing the number of iterations necessary for convergence and the comparison of the actual results with those generated by a priviously established numerical proceedure which ignores axial conduction. Besides the usual

geometric and physical/thermal properties of the gas and solid, the porosity, the velocity field, the Nusselt number and eddy diffusivity, E, must be specified in order to generate a solution. Using a reasonable value for Nu; setting E to zero; and as required by the analytical solution, assuming the velocity and porosity are constants, (U/Vo = 1 and = 0.4), the numerical proceedure as presented in this paper was applied. As for boundary condition, the gas and solid were assumed at a given temperature at a given temperature at the inlet as well as at the wall.

Although the discretization method as described by equations (8.) and (9.) was found to be quite satisfactory, in our first attempts to achieve a solution, an alternate method was also considered. This alternate method is equivalent to employing (8.) and (9.) except that the nodal temperatures multiplying the coefficients U1, U2, V1, V2, were considered at the $(k-1)^{st}$ iteration. The obvious superiority of the method represented by (8.) and (9.) is reflected in figure 4 . The advantages are shown in two ways: (i) a much lower number of iterations is necessary for convergence and (ii) the first method is less sensitive to changes in WS than the second. What may also be seen in figure 4. is an agreement with the assertion that for an elliptic equation with constant coefficients, the WS that results in the minimum number of iterations, lies between 1 and 2. This is seen to hold even for a variety of Re.

The method of calculation having been established, it remains, as a further check, to compare the results of the numerical solution presented here, (assuming constant porosity, velocity and an isothermal wall concition), to those results given by an associated numerical solution which has already been developed and which ignores axial conduction. This numerical proceedure is based on the parabolic mathematical equations which one obtains when axial conduction is ignored. Such a system has the numerical advantage that the solution can be found directly without iteration. The results of the numerical solutions for a Re of five thousand are shown in figure 5. In addition, the results of the previous numerical solution ignoring axial conduction; are compared to an analytical solution which ignores axial conduction by construction as well and which can be generated in terms of Bessel functions. This comparison is almost exact. As the difference between the numerical proceedures is the inclusion of axial conduction, it follows that the difference in the num-

erical results is due to the conduction of heat in opposition to the direction of the flow. Looking at the non-dimensional equation (5.), one sees that the product Re•Pr determines the relative importance of the convective terms relative to the conductive terms. Therefore as the Re increases, one would expect that the diffusive terms play an increasingly less significant role and as figure 6. shows, that the numerical solutions should approach one another. Thus for Re•Pr down to about 750 the solution given by the numerical proceedure including axial conduction should approximate the numerical solution excluding axial conduction to within 1% . This implies that there exists, for given parameters, a Re, above which the simpler parabolic system of equations can be used; and below which the more complex elliptic system must be employed. However, as seen in figure 7., this relative error does not exhibit a uniform distribution, but is a function of the position of the bed. The result that the relative maxima of error occurr near the exit and near the wall of the bed, can be explained by figure 8. . Figure 8. shows that the second derivative of the gas temperature is highest near the bed exit and near the bed wall; and therefore one would expect that in these regions the relative discrepency between the numerical solutions would be greatest.

It is seen, therefore, that the numerical proceedure described in this paper can be optimized in the sense that the number of iterations are minimized, by keeping WS between 1 and 1.2 . In addition, the agreement between the results of the numerical approach presented here and the results of the numerical proceedure which ignored axial conduction, being shown to become better as the Re increases, serves to justify that the program is operating properly.

4. Study of the Formation of Hot Spots Due to Variations in the Porosity Distribution

In order to better simulate the local properties of a packed bed and its heat transfer characteristics, experimental expressions for the porosity, given as equation (3.), for the local Nusselt number, given in appendix C1, and expressions for parabolic and turbulent superficial velocity profiles are used. The expressions used for the velocity profiles are given in appendix C2 and are graphed along with the porosity and Nusselt number distributions in figures 9. and 10. respectively. The

oscillatory variation of the porosity is a result of the influence of the wall containing the packed bed. The porosity is 1 by definition at the wall and as the center is approached the porosity becomes a constant value, (typically 0.4 for a lightly packed random bed). Figure 11. shows the gas temperature obtained at the exit of the bed for a constant velocity profile and type (i) boundary conditions, (see below). The oscillatory variations observed are due to the variations in the porosity distribution. This can be explained by realizing that regions of relatively low porosity are regions of high spherical density and therefore regions where high heat transfer rates between the solid and the gas exist. The dashed line in figure 11. , is the numerical solution given by the program that ignores axial conduction. It shows good agreement with the present solution. Figures 12. and 13. show the solution obtained at the bed exit for assumed turbulent and laminar velocity profiles respectively. Type (i) boundary conditions are used here also. Again the oscillatory variations are due to the local variation in porosity; but, in addition, due to the fact that the velocity is greater than the mean, up to a certain distance from the center, and is less than the mean nearer the wall, the cooling affects of the fluid are more efficient nearer the center than nearer the wall. Therefore the relative maxima in the temperature profiles are due to both the relative minima of porosity that occurr near the wall and to the inefficient cooling in this region. It should be mentioned that E was assumed zero in these cases involving figures 11., 12., 13. .

Assuming a turbulent velocity profile, figure 14. presents the resulting gas temperature distributions for a variety of boundary conditions. The boundary conditions used are defined as follows:

type (i): $Ts(0,r) = To,\ Ts = Tg(x,RT) = Ta$

type (ii): $\frac{\partial Ts}{\partial x}(0,r) = 0,\ Ts = Tg(x,RT) = Ta$

type (iii): $\frac{\partial Ts}{\partial x}(0,r) = 0,\ \frac{\partial Ts}{\partial r} = \frac{\partial Tg}{\partial r}(x,RT) = 0$;

other boundary conditions remain as previously described and are the same for each of these cases.

It can be seen that by changing from a type (i) to a type (ii) boundary condition, the temperature profile of the gas increases yet keeps the general shape of the isothermal case and that the position of the hot spot has kept the same position. With the introduction of the type (iii)

boundary condition, the opportunity for heat to be passed through the wall is lost. Therefore, as expected, the temperature profile is raised even further. In addition, the hot spot is moved significantly closer to the wall.

It should be mentioned in passing, that as with the results in figures 11., 12., and 13. the dashed line in figure 14., is calculated using a Nusselt number based on the mean Re; whereas the other curves in figure 14. are calculated using a Nusselt number based on the local Re. The shift to a local Nu slightly raises the temperature profile due to the fact that the local Re (and therefore the local Nu), is greater than the mean Re, (mean Nu), for most of the radial dimension. This allows a larger heat transfer between the solid and the gas which raises the resulting temperature profile.

Earlier, the results of the numerical technique developed in this paper compared to a previously established numerical technique, (ignoring axial conduction), which in turn was seen to be identical to an associated analytical solution. The results of the numerical proceedures were seen to approach one another as the Re increased. This implied that the numerical proceedure including axial conduction was implimented properly. To attempt to justify the numerical results, one must compare them with experimental ones. Such experimental work was done at the Von Karman Institute and is discussed in reference (5). Using their given data, numerical calculations were made. The experimental and numerical results appear in figure 15. . As the temperatures are scaled with respect to the hot spot temperature, only the predicition of the position of the hot spot can be made and not its magnitude. Considering that the experimental data was in the form of a temperature map of the bed exit and that one necessairly must choose the radial profile to compare his numerical results with, (the radial profile through the hot spot of the bed exit was taken) and that one cannot expect the porosity of the experimental packed bed to be the same as that used in the numerical program, that the numerical results rather successfully predicted the radial position of the hot spot as well as the profiles' general shape, can be inferred. An additional point should be mentioned concerning figure 15. . As the bed height is increased, the level of temperature at the exit is raised and therefore the greater the heat loss through the wall. This accounts for the inward movement of the hot spot.

It is seen, then, that the variation in porosity introduces hot spot regions that exist close to the wall of the packed bed and that assumed parabolic or turbulent velocity profiles amplify the magnitude of these hot spots. In addition, the affect of employing adiabatic wall conditions tends to increase even more the temperature of these regions.

As a final point, the results presented in fighures 14. and 15., unlike figures 11., 12., 13., were calculated using a value of 20 for the modified Peclet number, Pe'. This value, dependent upon the Re and the ratio Dp/RT, is obtained from the experimental data given in reference (1). Because, (i) the value of Pe' determines the eddy diffusivity, E, which in turn contributes to the effective thermal conductivity kg*, and (ii) the greater the value of kg*, the greater the dissipative capacity of the gas is to damp out rapid temperature variations, it is important to be able to represent Pe' satisfactorily if one wants to predict the magnitude of hot spots. As an example, the calculated curve of figure 15., for HT/Dp = 10, is repeated in figure 16. and compared to a solution calculated from the same data save that the Pe' is very large, (therefore implying E = 0).

As the assumed axial velocity profile, or for that matter the "true" local mean axial velocity profile, would not be expected to show great variations in the radial direction, which would cause relatively large eddy diffusivities to arrise, the use of a constant E seems reasonable. However if one assumes a blockage exists, large perturbations in the flow field would result; thereby causing large gradients and therefore larger eddy diffusivities. In addition, as there would be little mass flow in the vicinity of the blockage, the conductive terms would become the main heat transfer process, whatever the bulk Re. Therefore only the application of the numerical proceedure including axial conduction, as presented here, would be justified.

5. Study of the Formation of Hot Spots Due to the Presence of Blockages

In the operation of a packed bed heat exchanger, a blockage concievably might result from the retention of dust/foreign matter being convected by the gas. In the region of the blockage, both the inefficient cooling by the gas and the heating of the dust surrounding the active spheres, would lead to the formation of a hot spot. The blockage, itself, is introduced into the program as a region of the relatively low porosity of 0.1 . Outside the blocked region the porosity is 0.4 . To avoid large gradients, a linear variation in the porosity between the blockage and the rest of the bed is used. See figure 16. for a clarifying illustration. The local velocity vector, (axial and radial components), is calculated by a program that solves the non-dimensional form of the Ergun equation. Refer to reference (6) for the equation and examples if its applications. The velocity field, for the case of the blockage, is shown in figure 17. . As expected the flow tends to be diverted around the blockage, thereby leaving the blocked region with little mass flow through it.

Unlike the previous cases where E was assumed constant over the entire field, we would expect relatively large velocity gradients in the case of the blockage and therefore regions of higher eddy diffusivities. A velocity gradient model relating E to the velocity field is used and is explained in appendix D.

Using the velocity gradient model for eddy diffusivity, the above definition for porosity, the Nusselt number expression in appendix C1 and the calculated velocity field, temperature distributions were obtained for a variety of cases.

Figure 18. shows axial and radial gaseous temperature curves for constant as well as variable E, using an isothermal wall condition. It must be mentioned that in calculating the variable eddy diffusivity distribution from the velocity field, an arbitrary constant multiplying the vector components of E, Ex and Er, was adjusted so that the vectoral sum of the average Ex and the average Er over the entire bed mesh, was such that the effective Pe' calculated from this mean value, matched the Pe' given in reference (1). As figure 18. shows, the presence of a blockage causes a signigicant temperature peak in the radial profile and effects an acceleration in the, what would otherwise be a linear temperature profile.

The variable E solution gave larger estimates of peak temperatures than the constant E solution. This can be explained by noting in figure 19. that in the region of the peak of the radial temperature curve, the E estimated by the variable model is much lower than the mean bed value. Hence less turbulence and less efficient cooling is the result and therefore the variable E model will give greater temperatures. Identical arguments can explain the discrepency between the axial temperature profiles of figure 18. when one notes that as with the upper curve in figure 19., the lower one shows that the variable E is much less than the mean value in the region of interest.

As mentioned in chapter , the expression $ks^* = (1 - \epsilon)\cdot ks$, does not take into account that ks* really depends on the number of contact points between spheres rather than exclusively on the porosity. One would expect, then, that ks* would in reality be somewhat less than that given by the above expression. Figure 20. shows the radial temperature at the bed exit for the same blockage case as treated before, (given as dots (•)), and compares this result with those profiles calculated by assumming subsequently lower values of ks. Because of increasing resistence to conductive heat flow, the model predicts subsequently larger peak temperature values as ks decreases.

The affect of employing a type (iii), adiabatic, wall condition as opposed to an isothermal one, has virtually no affect on the characteristics of the mid-bed radial profile, as exemplified by the upper curve in figure 21. . Not only is this ineffectuality in changing peak temperature values true at the mid-bed position, but it is true for the entire bed.

The lower curve in figure 21. shows that as the blockage is moved closer to the bed exit, the temperature peak at the bed rises accordingly. This brings up the immediate concern that temperature peaks may develope inside a packed bed with a blockage that may exceed the temperatures realized at the bed exit; and as it is difficult to determine temperatures inside an operating packed bed heat exchanger, these temperatures may go undected. The results from which the lower curve in figure 21. was derived, justify this concern; for as the blockage is in either the lower, middle, or upper position, the maximum gaseous temperature in the blocked region attains 89.5%, (at x = 0.47 HT), 95.5%, (at x = 0.63 HT) and 99.9%, (at x = 0.70 HT), of the maximum value of the exit temperature respectively.

It is therefore seen, then, that the introduction of blockages into packed beds, result in large peaks in the temperature field distribution. By using a velocity gradient model for the eddy diffusivity, E, the temperature peaks have been higher than might have otherwise been expected had a constant E been used. These hot spots may attain higher values, still, if one assumes that the effective thermal conductivity of the solid is lower than that given by the assumed expression. The magnitude of these peaks, in addition, are functions of the position of the blocked region; and it was seen that the possibility definitely exists that the magnitude of hot spots may be greatest inside the bed, itself, and therefore difficult to detect.

6. Summary and Conclusions

Envisioning the use of an active packed bed in a nuclear reactor, the concern of hot spot development due to porosity variation or due to the presence of blockages, is raised. It would be useful, therefore, to be able to calculate the resulting temperature field assuming that these porosity variations or blockages occurr. To that end, a two phase axis-symmetric mathematical model for heat transfer in an active packed bed was proposed. As axial conduction is considered, the resulting equations are elliptic and if calculations are to be done efficiently, these equations must be solved by an iteration proceedure. A method of over-relaxation by lines was employed and whose arbitrary coefficient of relaxation was chosen so as to approximately minimize the number of iterations needed for convergence. A numerical proceedure, which ignores axial conduction, which was shown essentially identical with an associated analytical solution, gave results which approached the numerical values of the present program as the Reynolds number increased. As the relative difference between the two solutions was on the order of 3-4% for low Re and decreased to approximately 1% for moderate Re, the results of the numerical solution were verified.

Concerning the case where variable porosity is assumed, it was seen that temperature peaks developed close to the bed wall. The position and magnitude of these hot spots was seen to be a strong function of the assumed velocity profile, the bed height, as well as the boundary conditions at the wall. The present solution was also seen to be in close agreement with the results of the previous program which ignores axial conduction. It is

in this respect that the following is proposed. For as most industrial uses insure Re of sufficient magnitude to assure that the inclusion of axial conduction would give temperatures of 90-95% of the ones given by the program excluding axial conduction and as the elliptic equations involve more complicated, time-consumming methods, it would perhaps be more efficient to base a design method on a mathematical model ignoring axial conduction, keeping in mind that the results are to some degree an upper limit to the "actaul temperatures". This concept of the questionable usefulness of the inclusion of the axial conduction, however, cannot be applied to the case where blockages are present.

As demonstrated, even for relatively large bulk Re, the mass flow inside the blockage itself was small and therefore, in the blocked region, heat transfer by conduction will play the major role. The blockage introduced a substantial peak in the radial temperature profile through the blockage itself. The overall maximum temperature, however, was still at the bed exit; even though it was approached by the maximum blockage temperature as the blockage moved downstream. It bears looking into the possibility that the maximum blockage temperature may exceed the maximum exit temperature by effecting changes in the position and size of a blockage.

As a final point, it was mentioned that the actual ks* may be lower than assumed. It was demonstrated that by lowering ks* the peak of the radial exit temperature profile was raised. It would therefore be useful to investigate the true nature of ks* so as one could place more certainty on whether a proposed design for the operation of an active packed bed is acceptable if one assumes the presence of a blockage.

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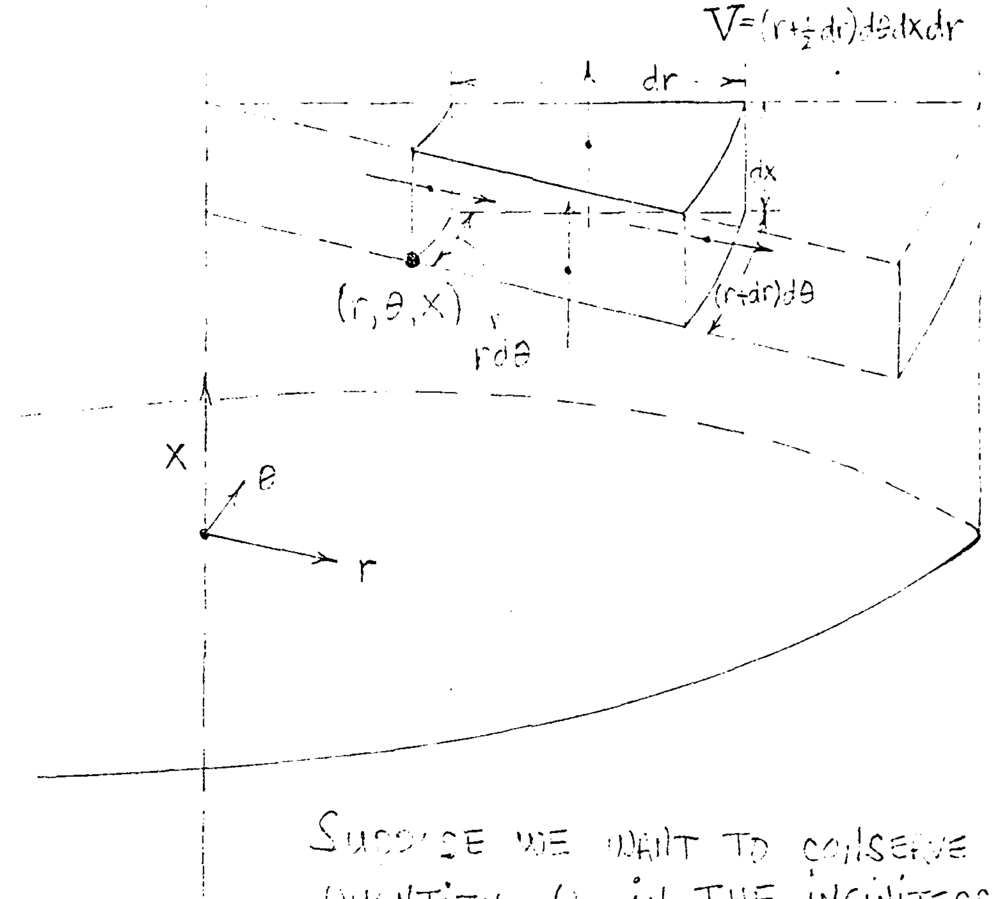
APPENDICIES

DEVELOPMENT of DIFFERENTIAL EQUATIONS

A.



SUPPOSE WE WANT TO CONSERVE THE QUANTITY Q IN THE INFINITESSIMAL VOLUME V. TAKING THE OUTWARD NORMAL AS POSITIVE, AND IGNORING VARIATIONS IN THE θ DIRECTION, THE NET FLUX OUT OF V OF Q, IS GIVEN BY THE FOLLOWING EQUATION.

$$(\text{FLUX})_Q = Q_{r+dr}\cdot A_{r+dr} - Q_r\cdot A_r + Q_{x+dx}\cdot A_{x+dx} - Q_x\cdot A_x$$
$$= Q_{r+dr}\cdot(r+dr)d\theta dx - Q_r\cdot r\,d\theta dx + (Q_{x+dx} - Q_x)(r+\tfrac{1}{2}dr)d\theta dr \Rightarrow$$

$$\frac{(\text{FLUX})_Q}{V} = \frac{(Q_{r+dr} - Q_r)\cdot r}{(r+\frac{1}{2}dr)dr} + \frac{Q_{r+dr}}{r+\frac{1}{2}dr} + \frac{(Q_{x+dx} - Q_x)}{dx}\ ; \quad \text{let } dx, d\theta, dr \to 0$$

$$= \frac{\partial Q_r}{\partial r} + \frac{Q_r}{r} + \frac{\partial Q_x}{\partial x} = \frac{1}{r}\cdot\frac{\partial}{\partial r}(r\cdot Q_r) + \frac{\partial Q_x}{\partial x}$$

... HEAT TRANSFER IN AN ACTIVE PACKED BED

... ARE THE TWO TYPES OF ENERGY FLUXES ACCROSS THE FACES OF ∇ THAT SHALL BE CONSIDERED: CONVECTIVE AND CONDUCTIVE FLUXES FOR THE GAS AND CONDUCTIVE FLUXES FOR THE SOLID (SINCE THE PARTICLES DO NOT MOVE).

a) FOR THE GAS THERE MUST BE A BALANCE BETWEEN THE NET FLUX OUT OF ∇ WITH THAT WHICH IS DELIVERED TO THE GAS ACCROSS THE SURFACE OF THE SPHERES:

CONVECTIVE FLUX $\begin{cases} Q_x = \rho u C_p T_g \\ Q_r = \rho V C_p T_g \end{cases}$

CONDUCTIVE FLUX $\begin{cases} Q_x = -k^*_{gx} \cdot \dfrac{\partial T_g}{\partial x} \\ Q_r = -k^*_{gr} \cdot \dfrac{\partial T_g}{\partial r} \end{cases}$

FLUX ACCROSS SPHERES SURFACE $\Big\}$ $h_v \cdot (T_s - T_g)$; $\therefore$

$$-\frac{\partial}{\partial x}\left(k^*_{gx} \cdot \frac{\partial T_g}{\partial x}\right) - \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot k^*_{gr} \cdot \frac{\partial T_g}{\partial r}\right) + \rho u c_p \frac{\partial T_g}{\partial x} + \rho V c_p \frac{\partial T_g}{\partial r}$$
$$+ \rho c_p T_g \frac{\partial u}{\partial x} + \rho c_p T_g \frac{\partial V}{\partial r} + \rho V c_p T_g / r = h_v (T_s - T_g)$$

ASSUMING INCOMPRESSIBLE FLOW:

$$\nabla \cdot (\underline{V}) = \frac{\partial u}{\partial x} + \frac{1}{r} \cdot \frac{\partial}{\partial r}(rV) = 0. \Rightarrow$$

$$-\frac{\partial}{\partial x}\left(k_{gx}^{*}\cdot\frac{\partial T_g}{\partial x}\right)-\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot k_{gr}^{*}\cdot\frac{\partial T_g}{\partial r}\right)+\rho u c_p\frac{\partial T_g}{\partial x}+\rho v c_p\frac{\partial T_g}{\partial r}$$
$$=h_v(T_s-T_g)$$

b) FOR THE SOLID THE PROCESS IS ANALOGOUS. AGAIN ONE MUST TAKE ACCOUNT OF THE CONDUCTIVE FLUXES AND BALANCE THEM WITH THE FLUX ACCROSS THE SPHERES SURFACE FROM THE GAS AND THE ENERGY PER UNIT SOLID VOLUME, Q', PRODUCED IN THE SPHERES THEMSELVES.

CONDUCTIVE FLUX $\begin{cases} q_x = -k_{sx}^{*}\cdot\frac{\partial T_s}{\partial x} \\ q_r = -k_{sr}^{*}\cdot\frac{\partial T_s}{\partial r} \end{cases}$

FLUX ACCROSS SPHERES SURFACE $\Big\}$ $h_v\cdot(T_g-T_s)$

ENERGY PRODUCED PER UNIT VOLUME PER SECOND $\Big\}$ $Q'\cdot(1-\epsilon)$; $\therefore$

$$-\frac{\partial}{\partial x}\cdot\left(k_{sx}^{*}\cdot\frac{\partial T_s}{\partial x}\right)-\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot k_{sr}^{*}\cdot\frac{\partial T_s}{\partial r}\right)$$
$$=h_v\cdot(T_g-T_s)+Q'\cdot(1-\epsilon).$$

WHERE k_s^{*} AND k_g^{*} ARE EFFECTIVE THERMAL CONDUCTIVITIES.

ASSUMPTIONS

(i) STEADY STATE INCOMPRESSIBLE FLOW

(ii) ρ, C_P, k_l, k_s, h_v, μ, $\dot{Q}'$ ARE INDEPENDENT OF TEMPERATURE

(iii) POROSITY BASED ON VOLUME EQUALS POROSITY BASED ON AREA.

(iv) POROSITY IS A CONTINUOUS FUNCTION

(v) THERMAL PROPERTIES WHOSE EXPERIMENTAL CORRELATIONS ARE BASED ON BULK POROSITY OR VELOCITY ARE STILL VALID WHEN LOCAL POROSITY OR VELOCITY IS USED.

(vi) VISCOUS DISSIPATION AND HEAT TRANSFER DUE TO RADIATION ARE NEGLECTED.

B. ANALYTICAL SOLUTION

$$T_g = T_w + \sum_n \left\{ \frac{2\cdot(T_0 - T_w)}{\lambda_n \cdot J_1(\lambda_n)} \cdot \exp\left(-\frac{\beta_n}{\alpha_n}\cdot x\right) + \frac{\sigma_n}{\beta_n}\cdot\left(1-\exp\left(-\frac{\beta_n}{\alpha_n}\cdot x\right)\right)\right\} \cdot J_0(\lambda_n r)$$

$$T_s = T_w + \sum_n \left\{ \frac{H}{(H+\lambda_n^2\cdot K)} \cdot \left[\frac{2\cdot(T_0 - T_w)}{\lambda_n \cdot J_1(\lambda_n)} \cdot \exp\left(-\frac{\beta_n}{\alpha_n}\cdot x\right) + \frac{\sigma_n}{\beta_n}\cdot\left(1-\exp\left(-\frac{\beta_n}{\alpha_n}\cdot x\right)\right)\right] + \frac{2\cdot S_0}{\lambda_n \cdot J_1(\lambda_n)\cdot(H+\lambda_n^2\cdot K)} \right\} \cdot J_0(\lambda_n r)$$

WITH

$$\frac{\beta_n}{\alpha_n} = \frac{\lambda_n^2 \cdot HT \cdot D_p}{RT^2} \cdot \left\{ \frac{\epsilon}{Re' \cdot Pr} + \frac{1}{Pe} + \frac{1}{\dfrac{Re'\cdot Pr}{K_s/k_g} + \dfrac{\lambda_n^2}{6\cdot(1-\epsilon)}\cdot\left(\dfrac{D_p}{RT}\right)^2 \cdot \left(\dfrac{Re'\cdot Pr}{Nu}\right)} \right\}$$

$$\frac{\sigma_n}{\beta_n} = \frac{2\cdot S_p \cdot RT^2}{\lambda_n^3 \cdot J_1(\lambda_n)\cdot K_s} \cdot \left\{ \frac{1}{1+\left[\dfrac{\lambda_n^2}{6\cdot(1-\epsilon)\cdot Nu}\left(\dfrac{D_p}{RT}\right)^2 + \dfrac{1}{K_s/k_g}\right]\cdot\left[\epsilon + \dfrac{Re'\cdot Pr}{Pe}\right]} \right\}$$

WHERE $\lambda_n : J_0(\lambda_n) = 0$

$Re' = D_p \cdot Re/RT$

$Pe = V_0 \cdot D_p / E$

$K_s/k_g = (1-\epsilon)(k_s/k_g)$

$S_p/K_s = Q'/k_s$

$H = 6\cdot(1-\epsilon)\cdot Nu \cdot (RT/D_p)^2 / \left(\epsilon + \frac{Re\cdot Pr}{Pe}\cdot(D_p/RT)\right)$

$K = (1-\epsilon)\cdot(k_s/k_g) / \left(\epsilon + \frac{Re\cdot Pr}{Pe}\cdot(D_p/RT)\right)$

$S_0 = S_p \cdot K \cdot RT^2 / K_s$

C1. NUSSELT NUMBER RELATIONSHIP

if $\nu = 1-\epsilon$

$\beta = (\alpha)^{1/3}$

$\gamma = 2 - 3\cdot\beta + 3\cdot(\beta)^5 - 2\cdot(\beta)^6$

THEN

$$Nu = 1.6\cdot\left\{ \frac{Re_{DO}\cdot Pr}{\epsilon\cdot\gamma}\cdot\left[1-(\alpha)^{5/3}\right]\right\}^{1/3}$$

C2. SUPERFICIAL VELOCITY PROFILES

if $US = U/V_0$, THEN FOR

(i) CONSTANT VELOCITY: $US = 1.$

(ii) TURBULENT VELOCITY PROFILE:

if $FLD = 0.079/(RE_{RT})^{1/4}$

$RFLD = [FLD/2]^{1/2}$

$REF = RE_{RT}\cdot RFLD$

$YP = REF\cdot(1 - r/RT)$

$RA = 1 - 30/REF$

$RB = 1 - 5/REF$

THEN

(CONTINUED)

FOR $0 \le r/RT < RA$

$$US = RFLD \cdot \left\{ 5.5 + 2.5 \cdot \mathrm{Log}\left[YP \cdot \frac{(1.5 \cdot (1 + r/RT))}{1 + 2 \cdot (r/RT)^2} \right] \right\}$$

FOR $RA \le r/RT < RB$

$$US = RFLD \cdot \left\{ -3.05 + 5 \cdot \mathrm{Log}(YP) \right\}$$

FOR $RB \le r/RT \le 1$

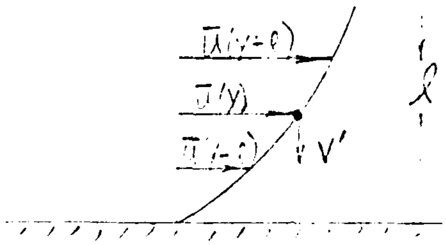
$$US = RFLD \cdot YP.$$

(iii) LAMINAR VELOCITY PROFILE

$$US = 2 \cdot (1 - (r/RT)^2)$$

D. VELOCITY GRADIENT MODEL FOR EDDY DIFFUSIVITY

REYNOLDS STRESS $= -\rho\,\overline{u'v'} \equiv \tau_{app}$



$|u'| = |\bar{u}(y) - \bar{u}(y-\ell)|$; REPLACE ℓ BY Δy

$\dfrac{|u'|}{\ell} = \dfrac{|\bar{u}(y) - \bar{u}(y-\Delta y)|}{\Delta y}$; TAKE LIMIT $\Delta y \to 0$

$|u'| = \ell \cdot \left|\dfrac{\partial \bar{u}}{\partial y}\right|$. THIS MAKES THE ASSUMPTION THAT THE MIXING LENGTH, ℓ, IS OF INFINITESIMAL ORDER.

ASSUME
$$|v'| = C_1 \cdot |u'|$$
$$\overline{u'v'} = -C_2 \cdot \overline{|u'|} \cdot \overline{|v'|}$$
$$\tau_{app} \equiv \rho \cdot E_y\, \partial \bar{u}/\partial y$$

THEN
$$\tau_{app} = -\rho\,\overline{u'v'}$$
$$= -\rho \cdot [-C_2 \cdot \overline{|u'|} \cdot C_1 \cdot \overline{|u'|}\,]$$
$$= \rho \cdot C_1 \cdot C_2 \cdot \ell^2 \cdot \left|\frac{\partial \bar{u}}{\partial y}\right| \cdot \frac{\partial \bar{u}}{\partial y} \Rightarrow$$

$$E_y = \underline{\ell}^2 \cdot \left|\frac{\partial \bar{u}}{\partial y}\right| \quad \text{WHERE} \quad \underline{\ell}^2 = C_1 \cdot C_2 \cdot \ell^2.$$

SIMILARLY: $E_x = \underline{\ell}^2 \cdot \left|\dfrac{\partial \bar{v}}{\partial x}\right|$

Appendix E.

Program Listings and Sample Outputs

```
      DEFINE FILE 8=108=M:LO
      COMMON/BLKK/A1(41),B1(41),C1(41),D1(41),E1(41)
      COMMON/BLKE/A2(41),B2(41),C2(41),D2(41),E2(41)
      COMMON/FZ/Z(43,43),NSUP,NSUP
      DIMENSION W1(31,31),W2(31,31),SOLN1(31),SOLN2(31),EP(31),EPR(31),
     1PN(31),USA(31)
C
      READ (105,100) RT,HT,RE,PF,PNU,TKC,TKR
      FORMAT(7F10.0)
      READ(105,200)MMAX,NMAX,J99MAX,EPS,WS,DP,TA,QP,POR
 200  FORMAT(3I5,5F10.0,F7.5)
      READ (105,150) PE,TO,VIS,M9,RNGW,RNSW,RNSO,ALPHA,BETA
  150 FORMAT (3(E10.4),I3,3(E10.4),2(F4.1))
C
      WRITE (108,600) RT,HT,RE,PR,PNU,TKG,TKR,POR,PE,VIS
      WRITE (108,600) MMAX,NMAX,J99MAX,EPS,WS,DP,TA,TO,QP,M9
  600 FORMAT (1X,10(E12.4),/)
      WRITE (108,601) RNGW,RNSW,RNSO,ALPHA,BETA
  601 FORMAT (1X,5(E10.4),//)
C
C INITIALIZATION OF TEMPERATURES
      DO 5 I=1,MMAX
      DO 5 J=1,NMAX
      W1(I,J)=ALPHA
      W2(I,J)=BETA
    5 CONTINUE
      US=1.
      VS=0.
      E=DP*RE*VIS/(RT*PE)
      PORR=0.
      M1=MMAX-1
      N1=NMAX-1
      DX=1./FLOAT(M1)
      DR=1./FLOAT(N1)
      J99=0
      S=FLOAT(M1-1)*FLOAT(N1-1)
C DETERMINATION OF COEFFICIENTS IN DISCRETIZED EQUATIONS
    7 J99=J99+1
      DT1=0.
      DT2=0.
      DER1=0.
      DER2=0.
      DO 10 I=2,M1
      IP1=I+1
      IM1=I-1
      DO 20 J=2,N1
      CALL DATSW(1,ISW)
      GO TO (627,629),ISW
  629 CONTINUE
      IF (I .EQ. 2) GO TO 625
      POR=EP(J)
      PORR=EPR(J)
      PNU=PN(J)
      US=USA(J)
  625 R=FLOAT(J-1)*DR
      IF (I .GT. 2) GO TO 630
C
C FIND E(R)
C
      ZP=PT*(1.-R)/DP
      POP =0.4+0.3*(EXP(-3.5*ZR)+COS(6.28*ZR)*EXP(-0.8*ZR))
      PORP1=1.05*EXP(-3.5*ZR)
      PORP2=1.384*SIN(6.28*ZR)*EXP(-0.8*ZR)
```

```
      PORR3=0.24*COS(6.28*ZR)*EXP(-0.8*ZR)
      PORR=RT*(PORR1+PORR2+PORR3)/DP
      EP(J)=POR
      EPR(J)=PORR
C
  627 R= FLOAT(J-1)*DP
C
      IF (MP .EQ. 1) GO TO 90
      IF (MP .EQ. 3) GO TO 85
      US=2.*(1.-R**2.)
      GO TO 90
   85 FLD=0.079/(RE**0.25)
      RFLD=SQRT(FLD/2.)
      REF=RE*RFLD
      YP=REF*(1.-R)
C
      RA=1.-30./REF
      RB=1.-5./REF
C
      IF (R .GT. RA) GO TO 86
      US=RFLD*(5.5+2.5*ALOG(YP*(1.5*(1.+R))/(1.+2.*R*R)))
      GO TO 90
   86 IF (R .GT. RB) GO TO 87
      US=RFLD*(-3.05+5.*ALOG(YP))
      GO TO 90
   87 US=RFLD*YP
   90 USA(J)=US
      REB=RE*DP*US/RT
C
C FIND NU(RE,E(R))
C
      C=1.-POR
      O2=C**0.33333
      O1=2.-3.*O2+3.*O2**5.-2.*O2**6.
      PNU=1.6*((REB*PR/(POR*O1))*(1.-C**1.66667))**0.33333
C
      PN(J)=PNU
C
C CALCULATE COEFFICIENTS IN EQUATIONS
C
  630 AA1=RT*(POR+PR*E/VIS)/(RE*PR*HT*HT)
      AA2=RT*(1.-POR)*TKR/(RE*PR*HT*HT)
      CC1=RT*(POR+PR*E/VIS)/(RE*PR*RT*RT)
      CC2=RT*(1.-POR)*TKR/(RE*PR*RT*RT)
      H=6*(1.-POR)*PNU*RT/(RE*PR*DP*DP)
      Q=RT*QP*(1.-POR)/(RE*PR*TKG*TO)
      V1=-CC1/R-RT*PORR/(RE*PR*RT*RT)+VS/RT
      V2=-CC2/R+RT*PORR*TKR/(RE*PR*RT*RT)
      U1=US/HT
      U2=0.
C
      A1(J)=-CC1/DR/DR-V1/DR/2.
      B1(J)=2.*(AA1/DX/DX+CC1/DR/DR)+H+U1/DX
      C1(J)=-CC1/DR/DR+V1/DR/2.
      D1(J)=H
      E1(J)=W1(IM1,J)*(AA1/DX/DX+U1/DX)+W1(IP1,J)*(AA1/DX/DX)
C
      A2(J)=-CC2/DR/DR-V2/DR/2.
      B2(J)=2.*(AA2/DX/DX+CC2/DR/DR)+H+U2/DX
      C2(J)=-CC2/DR/DR+V2/DR/2.
      D2(J)=H
      E2(J)=W2(IM1,J)*(AA2/DX/DX+U2/DX)+W2(IP1,J)*(AA2/DX/DX)+Q
C
   20 CONTINUE
C
C ADJUST COEFFICIENTS SO AS TO SATISFY BOUNDARY CONDITIONS
C
      B1(2)=B1(2)+A1(2)
      B2(2)=B2(2)+A2(2)
      B1(N1)=B1(N1)+C1(N1)/(1.+DR*RT*RNGW)
      E1(N1)=E1(N1)-C1(N1)*DR*RT*RNGW*TA/(TO*(1.+DR*RT*RNGW))
      B2(N1)=B2(N1)+C2(N1)/(1.+DR*RT*RNSW)
      E2(N1)=E2(N1)-C2(N1)*DR*RT*RNSW*TA/(TO*(1.+DR*RT*RNSW))
C
C EXECUTE SOLUTION TECHNIQUE TO SOLVE COUPLED TRIDIAGONAL SYSTEM
C
      CALL TRISBU (NMAX,SOLN1,SOLN2)
C
C EXECUTE RELAXATION TECHNIQUE IN ORDER TO UPDATE UNKNOWN VALUES
C
```

```
      DO 30 J=2,N1
      SN1=W1(I,J)+WS*(SOLN1(J)-W1(I,J))
      SN2=W2(I,J)+WS*(SOLN2(J)-W2(I,J))
      ERR1=ABS(SN1-SOLN1(J))
      ERR2=ABS(SN2-SOLN2(J))
      DT1=DT1+ERR1/S
      DT2=DT2+ERR2/S
C FIND MAXIMUM ERROR IN THE NET AND ITS POSITION
      CALL CONV2(I,J,ERR1,ERR2,LI1,LI2,LJ1,LJ2,DER1,DER2)
      W1(I,J)=SN1
      W2(I,J)=SN2
   30 CONTINUE
      W1(I,1)=W1(I,2)
      W2(I,1)=W2(I,2)
      W1(I,NMAX)=(W1(I,N1)+DR*RT*RNGW*TA/TO)/(1.+DR*RT*RNGW)
      W2(I,NMAX)=(W2(I,N1)+DR*RT*RNSW*TA/TO)/(1.+DR*RT*RNSW)
   10 CONTINUE
      DO 35 J=1,NMAX
      W1(MMAX,J)=W1(M1,J)
      W2(MMAX,J)=W2(M1,J)
      W1(1,J)=1.
      W2(1,J)=(DX*HT*RNSO+W2(2,J))/(1.+DX*HT*RNSO)
   35 CONTINUE
      IF (J99 .LE. 30) GO TO 38
      GO TO 39
   38 WRITE(108,300) J99,LI1,LJ1,DER1,LI2,LJ2,DER2
  300 FORMAT(1X,2HK=, I3,3H M=, I2,3H N=, I2, 9H ERRMAX1=, E12.6,
     1 2X,2HX=, I2,3H R=, I2, 9H ERRMAX2=, E12.6,/)
      WRITE(108,400) DT1,DT2
  400 FORMAT(1X,9HERRAVG1=, E12.6,10H  ERRAVG2=, E12.6,/)
   39 CONTINUE
      IF (J99 .GT. J99MAX) GO TO 40
      IF (DT1 .GT. EPS) GO TO 7
      IF (DT2 .GT. EPS) GO TO 7
   40 CONTINUE
      IF (J99 .LE. 30) GO TO 45
      WRITE(108,300) J99,LI1,LJ1,DER1,LI2,LJ2,DER2
      WRITE(108,400) DT1,DT2
   45 CONTINUE
C
      WRITE (108,500) (USA(J),J=2,N1)
      WRITE (108,500) ( EP(J),J=2,N1)
      WRITE (108,500) ( PN(J),J=2,N1)
C
C THE SOLUTION FOLLOWS
C
      WRITE (108,450)
  450 FORMAT(/,1X,47HTEMPERATURE DISTRIBUTIONS FOR THE GAS AND SOLID,//)
      DO 55 K=1,MMAX
      L=MMAX-K+1
      WRITE (108,500) (W1(L,J),J=1,NMAX)
      WRITE (108,800) (W2(L,J),J=1,NMAX)
  500 FORMAT (2X,11F9.4,/)
  800 FORMAT (1X,1H+,11F9.4,//)
   55 CONTINUE
C
      WRITE(108,460)
  460 FORMAT(1H1)
      MSUP=MMAX+1
      NSUP=NMAX+1
      DO 948 I=2,MSUP
      DO 948 J=2,NSUP
      Z(I,J)=W1(I-1,J-1)
  948 CONTINUE
      CALL BUNIV
      DO 950 I=2,MSUP
      DO 950 J=2,NSUP
      Z(I,J)=W2(I-1,J-1)
  950 CONTINUE
      CALL BUNIV
      END
```

HCT

```
     RT           HT           Re           Pr           Nu           kf          ks/kf       porosity       le'       kin. vis.
  .5000E-01    .1000E+00    .5000E+04    .7200E+00    .5144E+02    .2500E-01    .1000E+03    .4000E+00    .2000E+02    .1520E-04
     V                       iter. max     error         nS          Di           Ta           Tp           w
  .3100E+02    .2100E+02    .2000E+03    .1000E-03    .1100E+01    .1000E-01    .2000E+02    .1500E+02    .4000E+06    .3000E+01
   hgw          hsw          hsi
 .1000E+11   .1000E+11    .1000E+11    .1000E+01    .1000E+01

K=  1 X=30 R=20 ERRMAX1=  .227570E-01  X=30 R=20 ERRMAX2=  .192099E-01
ERRAVG1=  .673499E-02  ERRAVG2=  .113569E-01
K=  2 X=30 R=19 ERRMAX1=  .962830E-02  X=30 R=19 ERRMAX2=  .123167E-01
ERRAVG1=  .499500E-02  ERRAVG2=  .887595E-02
K=  3 X=30 R=15 ERRMAX1=  .783356E-02  X=30 R=16 ERRMAX2=  .101500E-01
ERRAVG1=  .378969E-02  ERRAVG2=  .700379E-02
K=  4 X=30 R=15 ERRMAX1=  .647926E-02  X=30 R=14 ERRMAX2=  .864506E-02
ERRAVG1=  .293180E-02  ERRAVG2=  .555242E-02
K=  5 X=30 R=15 ERRMAX1=  .525570E-02  X=30 R=17 ERRMAX2=  .737190E-02
ERRAVG1=  .228050E-02  ERRAVG2=  .440557E-02
K=  6 X=30 R=15 ERRMAX1=  .422639E-02  X=30 R=13 ERRMAX2=  .621414E-02
ERRAVG1=  .177819E-02  ERRAVG2=  .349762E-02
K=  7 X=30 R=11 ERRMAX1=  .343132E-02  X=30 R=12 ERRMAX2=  .513894E-02
ERRAVG1=  .138534E-02  ERRAVG2=  .277260E-02
K=  8 X=30 R=11 ERRMAX1=  .279713E-02  X=30 R=12 ERRMAX2=  .430393E-02
ERRAVG1=  .109493E-02  ERRAVG2=  .220334E-02
K=  9 X=30 R=11 ERRMAX1=  .226794E-02  X=30 R=10 ERRMAX2=  .356102E-02
ERRAVG1=  .948227E-03  ERRAVG2=  .174735E-02
K= 10 X=30 R=11 ERRMAX1=  .182915E-02  X=30 R=10 ERRMAX2=  .293064E-02
ERRAVG1=  .163455E-03  ERRAVG2=  .178472E-02
K= 11 X=30 R=11 ERRMAX1=  .143961E-02  X=30 R= 9 ERRMAX2=  .240421E-02
ERRAVG1=  .518976E-03  ERRAVG2=  .109641E-02
K= 12 X=30 R=11 ERRMAX1=  .117697E-02  X=30 R= 9 ERRMAX2=  .196266E-02
ERRAVG1=  .405937E-03  ERRAVG2=  .867378E-03
K= 13 X=30 R=11 ERRMAX1=  .934369E-03  X=30 R= 9 ERRMAX2=  .159454E-02
ERRAVG1=  .317469E-03  ERRAVG2=  .685592E-03
K= 14 X=30 R=11 ERRMAX1=  .747691E-03  X=30 R= 9 ERRMAX2=  .129032E-02
ERRAVG1=  .248707E-03  ERRAVG2=  .541355E-03
K= 15 X=30 R=11 ERRMAX1=  .594139E-03  X=30 R= 9 ERRMAX2=  .104237E-02
ERRAVG1=  .194207E-03  ERRAVG2=  .427185E-03
K= 16 X=30 R= 7 ERRMAX1=  .473022E-03  X=30 R= 6 ERRMAX2=  .840187E-03
ERRAVG1=  .151744E-03  ERRAVG2=  .336746E-03
K= 17 X=30 R= 7 ERRMAX1=  .377655E-03  X=30 R= 6 ERRMAX2=  .676155E-03
ERRAVG1=  .119594E-03  ERRAVG2=  .265216E-03
K= 18 X=30 R= 7 ERRMAX1=  .302407E-03  X=30 R= 5 ERRMAX2=  .543594E-03
ERRAVG1=  .926572E-04  ERRAVG2=  .208727E-03
K= 19 X=30 R= 7 ERRMAX1=  .239419E-03  X=30 R= 5 ERRMAX2=  .435829E-03
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ERRAVG1= [illegible]E-04   ERRAVG2= .164163E-03
K= [illegible] X=30 R= 7 ERRMAX1= .10[illegible]E-03  X=30 R= 5 ERRMAX2= .349045E-03
ERRAVG1= .5[illegible]E-04   ERRAVG2= .1[illegible]005E-03
K= 21 X=30 R= 7 ERRMAX1= .14[illegible]E-03  X=30 R= 5 ERRMAX2= .279473E-03
ERRAVG1= .439734E-04   ERRAVG2= .101260E-03
K= 27 X=30 R= 7 ERRMAX1= .11125[illegible]E-03  X=30 R= 5 ERRMAX2= .22220[illegible]E-03
ERRAVG1= .743599E-04   ERRAVG2= .794771E-04
    1.4452   1.4414   1.4351   1.4263   1.4153   1.4020   1.3966   1.3691   1.3495   1.3278   1.30[illegible]
    1.2771   1.2475   1.2141   1.1757   1.1303   1.0737   0.9969   0.7646
    0.3939   0.3913   0.4301   0.4122   0.3995   0.3818   0.4002   0.4272   0.3997   0.3594   0.4005
    0.4619   0.4002   0.7112   0.4042   0.5439   0.4213   0.2510   0.5253
    [illegible]   [illegible]   55.5467  56.4431  53.3277  61.3235  57.9616  53.4017  57.4256  64.5041  56.647[illegible]
    17.7070  55.2572  73.5994  54.1429  37.4116  50.0517  87.2457  34.2975
 TEMPERATURE DISTRIBUTIONS FOR THE GAS AND SOLID
    1.5791   1.5791   1.5807   1.5806   1.5819   1.5838   1.5961   1.5969   1.5989   1.6114   1.6240
    1.6224   1.6171   1.6320   1.6448   1.6179   1.5842   1.5699   1.5443   1.4449   1.3333
 *  1.8610   1.8610   1.8619   1.8647   1.8682   1.8710   1.8742   1.8799   1.8860   1.8884   1.8894

 *  1.8975   1.8943   1.8848   1.8696   1.8562   1.8236   1.7609   1.6996   1.6279   1.3333
    1.5791   1.5791   1.5807   1.5806   1.5819   1.5838   1.5961   1.5969   1.5989   1.6114   1.6240
    1.6224   1.6171   1.6320   1.6448   1.6179   1.5842   1.5699   1.5443   1.4449   1.3333
 *  1.8610   1.8610   1.8619   1.8647   1.8682   1.8710   1.8742   1.8799   1.8860   1.8884   1.8894

 *  1.8975   1.8943   1.8848   1.8696   1.8562   1.8236   1.7609   1.6996   1.6279   1.3333
    1.5615   1.5615   1.5631   1.5629   1.5641   1.5709   1.5782   1.5790   1.5808   1.5934   1.6067
    1.6027   1.5996   1.6155   1.6275   1.6036   1.5716   1.5601   1.5378   1.4415   1.3333
 *  1.8522   1.8522   1.8531   1.8559   1.8594   1.8622   1.8653   1.8711   1.8773   1.8797   1.8807

 *  1.8851   1.8867   1.8770   1.8623   1.8496   1.8192   1.7566   1.6961   1.6255   1.3333
    1.5416   1.5416   1.5432   1.5429   1.5441   1.5508   1.5581   1.5587   1.5604   1.5731   1.5861
    1.5816   1.5799   1.5965   1.6118   1.5871   1.5570   1.5486   1.5300   1.4375   1.3333
 *  1.8381   1.8381   1.8390   1.8418   1.8453   1.8480   1.8511   1.8570   1.8632   1.8657   1.8668

 *  1.8715   1.8737   1.8646   1.8505   1.8391   1.8094   1.7497   1.6906   1.6215   1.3333
    1.5211   1.5211   1.5227   1.5223   1.5234   1.5301   1.5373   1.5378   1.5394   1.5521   1.5651
    1.5619   1.5591   1.5766   1.5931   1.5697   1.5416   1.5364   1.5216   1.4331   1.3333
 *  1.8210   1.8210   1.8220   1.8247   1.8282   1.8309   1.8340   1.8398   1.8461   1.8486   1.8500

 *  1.8551   1.8579   1.8495   1.8362   1.8261   1.7936   1.7412   1.6838   1.6165   1.3333
    1.5004   1.5004   1.5019   1.5015   1.5025   1.5091   1.5162   1.5166   1.5181   1.5307   1.5438
    1.5405   1.5381   1.5563   1.5739   1.5518   1.5257   1.5238   1.5128   1.4285   1.3333
 *  1.8023   1.8023   1.8032   1.8059   1.8094   1.8120   1.8151   1.8210   1.8273   1.8299   1.8314

 *  1.8399   1.8403   1.8328   1.8204   1.8119   1.7865   1.7317   1.6762   1.6110   1.3333
    1.4796   1.4796   1.4811   1.4806   1.4815   1.4880   1.4950   1.4952   1.4966   1.5091   1.5223
    1.5190   1.5169   1.5356   1.5542   1.5333   1.5093   1.5106   1.5036   1.4237   1.3333
 *  1.7826   1.7826   1.7835   1.7862   1.7896   1.7922   1.7952   1.8011   1.8074   1.8101   1.81[illegible]8

 *  1.8177   1.8219   1.8150   1.8037   1.7965   1.7736   1.7215   1.6680   1.6050   1.3333
    1.4537   1.4587   1.4601   1.4596   1.4604   1.4668   1.4736   1.4737   1.4749   1.4874   1.5005
    1.4972   1.4952   1.5146   1.5342   1.5144   1.4924   1.4970   1.4941   1.4197   1.3333
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*	1.7624	1.7624	1.7632	1.7659	1.7693	1.7718	1.7747	1.7806	1.7870	1.7898	1.7916
*	1.7979	1.8025	1.7966	1.7863	1.7805	1.7601	1.7108	1.6594	1.5987	1.3333	
	1.4377	1.4377	1.4381	1.4325	1.4392	1.4455	1.4522	1.4521	1.4532	1.4656	1.4796
	1.4753	1.4734	1.4933	1.5137	1.4951	1.4751	1.4829	1.4942	1.4135	1.3333	
*	1.7418	1.7418	1.7427	1.7453	1.7486	1.7510	1.7540	1.7598	1.7662	1.7690	1.7712
*	1.7776	1.7823	1.7777	1.7684	1.7641	1.7461	1.6997	1.6505	1.5921	1.3333	
	1.4127	1.4167	1.4181	1.4174	1.4181	1.4242	1.4308	1.4305	1.4315	1.4437	1.456
	1.4572	1.4514	1.4716	1.4929	1.4753	1.4572	1.4684	1.4739	1.4090	1.3333	
*	1.7211	1.7211	1.7219	1.7245	1.7279	1.7301	[illegible]	1.7388	1.7452	1.7480	1.7502
*	1.7570	1.7623	1.7584	1.7500	1.7472	1.7316	1.6882	1.6412	1.5852	1.3333	
	1.3957	1.3957	1.3971	1.3963	1.3969	1.4029	1.4093	1.4089	1.4096	1.4217	1.4345
	1.4310	1.4291	1.4499	1.4717	1.4551	1.4338	1.4537	1.4637	1.4024	1.3333	
*	1.7003	1.7003	1.7011	1.7036	1.7065	1.7091	1.7119	1.7176	1.7240	1.7269	1.7291
*	1.7362	1.7424	1.7388	1.7313	1.7300	1.7168	1.6763	1.6316	1.5782	1.3333	
	1.3747	1.3747	1.3761	1.3752	1.3756	1.3815	1.3878	1.3972	1.3378	1.3996	1.4123
	1.4066	1.4067	1.4276	1.4502	1.4344	1.4199	1.4377	1.4521	1.3965	1.3333	
*	1.6794	1.6794	1.6902	1.6826	1.6858	1.6880	1.6907	1.6963	1.7026	1.7055	1.7078
*	1.7151	1.7218	1.7199	1.7123	1.7123	1.7016	1.6640	1.6217	1.5709	1.3333	
	1.3539	1.3539	1.3550	1.3541	1.3544	1.3602	1.3663	1.3655	1.3658	1.3775	1.3900
	1.3861	1.3842	1.4052	1.4293	1.4132	1.4004	1.4215	1.4405	1.3903	1.3333	
*	1.6585	1.6585	1.6592	1.6616	1.6647	1.6668	1.6694	1.6750	1.6812	1.6840	1.6864
*	1.6939	1.7010	1.6997	1.6929	1.6943	1.6860	1.6514	1.6114	1.5633	1.3333	
	1.3328	1.3328	1.3340	1.3331	1.3332	1.3388	1.3448	1.3438	1.3439	1.3553	1.3676
	1.3635	1.3614	1.3926	1.4061	1.3916	1.3803	1.4047	1.4283	1.3838	1.3333	
*	1.6375	1.6375	1.6382	1.6406	1.6436	1.6456	1.6481	1.6535	1.6597	1.6624	1.6646
*	1.6724	1.6793	1.6781	1.6731	1.6759	1.6700	1.6383	1.6008	1.5554	1.3333	
	1.3119	1.3119	1.3130	1.3120	1.3120	1.3175	1.3232	1.3221	1.3220	1.3331	1.3452
	1.3409	1.3386	1.3597	1.3835	1.3695	1.3596	1.3872	1.4156	1.3769	1.3333	
*	1.6166	1.6165	1.6172	1.6195	1.6224	1.6243	1.6267	1.6320	1.6381	1.6408	1.6431
*	1.6508	1.6586	1.6573	1.6530	1.6571	1.6535	1.6248	1.5897	1.5472	1.3333	
	1.2908	1.2908	1.2920	1.2909	1.2909	1.2961	1.3017	1.3004	1.3000	1.3109	1.3227
	1.3161	1.3156	1.3366	1.3606	1.3470	1.3383	1.3689	1.4021	1.3696	1.3333	
*	1.5956	1.5956	1.5962	1.5984	1.6012	1.6030	1.6053	1.6105	1.6164	1.6190	1.6212
*	1.6290	1.6370	1.6362	1.6326	1.6379	1.6366	1.6109	1.5782	1.5387	1.3333	
	1.2699	1.2699	1.2710	1.2698	1.2697	1.2748	1.2802	1.2786	1.2780	1.2886	1.3001
	1.2953	1.2925	1.3133	1.3373	1.3239	1.3163	1.3498	1.3879	1.3618	1.3333	
*	1.5746	1.5746	1.5751	1.5773	1.5800	1.5817	1.5838	1.5889	1.5946	1.5971	1.5993
*	1.6071	1.6153	1.6148	1.6118	1.6183	1.6192	1.5964	1.5662	1.5298	1.3333	
	1.2489	1.2489	1.2500	1.2488	1.2485	1.2535	1.2587	1.2569	1.2561	1.2664	1.2775
	1.2724	1.2693	1.2898	1.3138	1.3005	1.2936	1.3298	1.3729	1.3534	1.3333	
*	1.5535	1.5535	1.5541	1.5562	1.5588	1.5603	1.5623	1.5672	1.5728	1.5751	1.5772
*	1.5850	1.5933	1.5931	1.5906	1.5982	1.6013	1.5813	1.5536	1.5204	1.3333	
	1.2280	1.2280	1.2291	1.2278	1.2274	1.2321	1.2371	1.2352	1.2341	1.2441	1.2549
	1.2495	1.2460	1.2661	1.2899	1.2765	1.2703	1.3089	1.3568	1.3444	1.3333	
*	1.5325	1.5325	1.5330	1.5350	1.5375	1.5389	1.5407	1.5455	1.5508	1.5530	1.5549

*	1.5617	1.5710	1.5711	1.5691	1.5776	1.5628	1.5655	1.5404	1.5106	1.3333	
	1.2071	1.2071	1.2081	1.2068	1.2063	1.2108	1.2156	1.2135	1.2122	1.2217	1.2322
	1.2266	1.2227	1.2423	1.2657	1.2522	1.2463	1.2869	1.3395	1.3345	1.3333	
*	1.5113	1.5113	1.5118	1.5138	1.5162	1.5174	1.5190	1.5236	1.5238	1.5307	1.5325
*	1.5482	1.5485	1.5487	1.5471	1.5566	1.5676	1.5491	1.5265	1.5002	1.3333	
	1.1862	1.1862	1.1872	1.1859	1.1952	1.1895	1.1941	1.1919	1.1903	1.1994	1.2095
	1.2076	1.1993	1.2193	1.2412	1.2275	1.2216	1.2638	1.3209	1.3237	1.3333	
*	1.4901	1.4901	1.4905	1.4924	1.4947	1.4958	1.4973	1.5017	1.5066	1.5083	1.5093
*	1.5175	1.5257	1.5260	1.5246	1.5349	1.5438	1.5318	1.5117	1.4891	1.3333	
	1.1653	1.1653	1.1663	1.1649	1.1642	1.1683	1.1727	1.1703	1.1685	1.1771	1.1868
	1.1867	1.1760	1.1942	1.2164	1.2024	1.1965	1.2394	1.3006	1.3116	1.3333	
*	1.4666	1.4686	1.4690	1.4709	1.4730	1.4739	1.4753	1.4795	1.4842	1.4856	1.4870
*	1.4934	1.5025	1.5027	1.5016	1.5126	1.5231	1.5135	1.4959	1.4772	1.3333	
	1.1445	1.1445	1.1455	1.1441	1.1433	1.1471	1.1512	1.1487	1.1467	1.1548	1.1640
	1.1578	1.1529	1.1700	1.1913	1.1771	1.1708	1.2138	1.2783	1.2979	1.3333	
*	1.4468	1.4468	1.4472	1.4489	1.4510	1.4517	1.4528	1.4569	1.4613	1.4625	1.4636
*	1.4739	1.4797	1.4798	1.4779	1.4894	1.5013	1.4939	1.4787	1.4643	1.3333	
	1.1237	1.1237	1.1247	1.1233	1.1225	1.1259	1.1298	1.1273	1.1251	1.1326	1.1412
	1.1350	1.1293	1.1457	1.1660	1.1517	1.1450	1.1869	1.2537	1.2821	1.3333	
*	1.4243	1.4243	1.4246	1.4263	1.4282	1.4238	1.4297	1.4335	1.4377	1.4385	1.4394
*	1.4463	1.4540	1.4539	1.4529	1.4650	1.4781	1.4727	1.4599	1.4499	1.3333	
	1.1030	1.1030	1.1040	1.1027	1.1019	1.1049	1.1084	1.1060	1.1038	1.1105	1.1183
	1.1124	1.1071	1.1215	1.1403	1.1263	1.1191	1.1587	1.2262	1.2638	1.3333	
*	1.4004	1.4004	1.4007	1.4023	1.4040	1.4044	1.4052	1.4087	1.4126	1.4131	1.4137
*	1.4203	1.4277	1.4272	1.4262	1.4386	1.4527	1.4491	1.4387	1.4337	1.3333	
	1.0816	1.0826	1.0335	1.0824	1.0814	1.0841	1.0872	1.0950	1.0827	1.0886	1.0956
	1.0900	1.0849	1.0975	1.1145	1.1011	1.0935	1.1294	1.1953	1.2419	1.3333	
*	1.3740	1.3740	1.3742	1.3757	1.3773	1.3775	1.3780	1.3813	1.3849	1.3851	1.3853
*	1.3916	1.3985	1.3977	1.3965	1.4090	1.4239	1.4219	1.4140	1.4144	1.3333	
	1.0626	1.0626	1.0634	1.0624	1.0615	1.0638	1.0664	1.0644	1.0623	1.0671	1.0731
	1.0681	1.0634	1.0738	1.0895	1.0765	1.0689	1.0994	1.1605	1.2151	1.3333	
*	1.3426	1.3426	1.3428	1.3442	1.3456	1.3457	1.3460	1.3490	1.3522	1.3520	1.3519
*	1.3577	1.3640	1.3629	1.3615	1.3739	1.3890	1.3886	1.3934	1.3903	1.3333	
	1.0433	1.0433	1.0440	1.0432	1.0425	1.0441	1.0462	1.0446	1.0428	1.0464	1.0511
	1.0472	1.0432	1.0511	1.0627	1.0523	1.0460	1.0694	1.1214	1.1816	1.3333	
*	1.3021	1.3021	1.3023	1.3035	1.3047	1.3046	1.3047	1.3073	1.3100	1.3096	1.3092
*	1.3142	1.3197	1.3193	1.3168	1.3284	1.3431	1.3444	1.3425	1.3570	1.3333	
	1.0255	1.0255	1.0260	1.0254	1.0249	1.0260	1.0273	1.0262	1.0250	1.0273	1.0305
	1.0277	1.0249	1.0300	1.0379	1.0310	1.0259	1.0409	1.0787	1.1393	1.3333	
*	1.2442	1.2442	1.2443	1.2453	1.2462	1.2460	1.2460	1.2480	1.2501	1.2494	1.2489
*	1.2529	1.2572	1.2556	1.2541	1.2639	1.2768	1.2797	1.2817	1.3054	1.3333	
	1.0103	1.0103	1.0105	1.0103	1.0100	1.0105	1.0111	1.0106	1.0100	1.0110	1.0125
	1.0112	1.0098	1.0121	1.0158	1.0125	1.0099	1.0164	1.0353	1.0803	1.3333	
*	1.1534	1.1534	1.1534	1.1539	1.1545	1.1543	1.1542	1.1554	1.1566	1.1561	1.1556
*	1.1580	1.1605	1.1593	1.1581	1.1643	1.1727	1.1759	1.1810	1.2113	1.3333	
	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

```
DP= 0.0050000      RT= 0.0500000      HT= 0.1000000
DENS=  .1211E+01      VISCO=  .1840E-04      RET= 4000.00      PR=  0.72
GK=   0.02500      SK=   0.75000      Q= 399999.98
TEX= 20.0      T0=15.00
M=   31      N=   31      NF=  100      NG=   20
OVER RELAXATION FACTOR= 1.40      TEST=      0.01
NJWG = *******      QWG =      0.00
NJWS = *******      QWS =      0.00
          BLOKAGE 1*
PMINA0 =    0.100   PMAXA0 =     0.400
I11A0 =   11   I22A0 =   21   J11A0 -   11   J4A0 =   21

          BLOKAGE 2*
PMINA1 =    0.100   PMAXA1 =     0.400
I11A1 =   50   I22A1 =   50   J11A1 =   50   J4A1 =   50
```

N=	1	DT =	.736E-02	DER =	.665E-01	POUR	I =20	ET	J =28
N=	2	DT =	.362E-02	DER =	.162E-01	POUR	I =18	ET	J =27
N=	3	DT =	.213E-02	DER =	.729E-02	POUR	I =16	ET	J =29
N=	4	DT =	.161E-02	DER =	.819E-02	POUR	I =19	ET	J =19
N=	5	DT =	.144E-02	DER =	.921E-02	POUR	I =18	ET	J =20
N=	6	DT =	.127E-02	DER =	.787E-02	POUR	I =17	ET	J =20
N=	7	DT =	.113E-02	DER =	.741E-02	POUR	I =16	ET	J =20
N=	8	DT =	.102E-02	DER =	.695E-02	POUR	I =16	ET	J =20
N=	9	DT =	.930E-03	DER =	.651E-02	POUR	I =15	ET	J =20
N=	10	DT =	.860E-03	DER =	.611E-02	POUR	I =15	ET	J =20
N=	11	DT =	.804E-03	DER =	.579E-02	POUR	I =14	ET	J =20
N=	12	DT =	.756E-03	DER =	.554E-02	POUR	I =13	ET	J =20
N=	13	DT =	.715E-03	DER =	.532E-02	POUR	I =13	ET	J =20
N=	14	DT =	.678E-03	DER =	.510E-02	POUR	I =13	ET	J =20
N=	15	DT =	.644E-03	DER =	.486E-02	POUR	I =13	ET	J =20
N=	16	DT =	.612E-03	DER =	.462E-02	POUR	I =13	ET	J =20
N=	17	DT =	.592E-03	DER =	.437E-02	POUR	I =13	ET	J =20
N=	18	DT =	.553E-03	DER =	.422E-02	POUR	I =12	ET	J =20
N=	19	DT =	.526E-03	DER =	.409E-02	POUR	I =12	ET	J =20
N=	20	DT =	.501E-03	DER =	.397E-02	POUR	I =12	ET	J =20
N=	21	DT =	.479E-03	DER =	.386E-02	POUR	I =12	ET	J =20
N=	22	DT =	.460E-03	DER =	.376E-02	POUR	I =12	ET	J =20
N=	23	DT =	.307E-03	DER =	.219E-02	POUR	I =11	ET	J =21
N=	24	DT =	.211E-03	DER =	.142E-02	POUR	I =11	ET	J =22
N=	25	DT =	.210E-03	DER =	.174E-02	POUR	I =19	ET	J =20
N=	26	DT =	.197E-03	DER =	.910E-03	POUR	I =18	ET	J =20
N=	27	DT =	.160E-03	DER =	.741E-03	POUR	I =12	ET	J =20
N=	28	DT =	.161E-03	DER =	.781E-03	POUR	I =16	ET	J =19
N=	29	DT =	.154E-03	DER =	.697E-03	POUR	I =15	ET	J =19
N=	30	DT =	.142E-03	DER =	.637E-03	POUR	I =14	ET	J =19
N=	31	DT =	.136E-03	DER =	.636E-03	POUR	I =13	ET	J =19
N=	32	DT =	.132E-03	DER =	.592E-03	POUR	I =15	ET	J =19
N=	33	DT =	.126E-03	DER =	.547E-03	POUR	I =14	ET	J =19
N=	34	DT =	.121E-03	DER =	.564E-03	POUR	I =13	ET	J =19
N=	35	DT =	.117E-03	DER =	.507E-03	POUR	I =12	ET	J =19
N=	36	DT =	.113E-03	DER =	.468E-03	POUR	I =14	ET	J =19
N=	37	DT =	.109E-03	DER =	.478E-03	POUR	I =13	ET	J =19
N=	38	DT =	.106E-03	DER =	.451E-03	POUR	I =13	ET	J =19
N=	39	DT =	.102E-03	DER =	.420E-03	POUR	I =13	ET	J =16
N=	40	DT =	.983E-04	DER =	.415E-03	POUR	I =13	ET	J =19

VITESSE AXIALE

1.4530420	1.4524543	1.4506978	1.4477825	1.4437258	1.4385521	1.4322889	1.4249676	1.4166164	1.4072627	
1.3969344	1.3956447	1.3734072	1.3602191	1.3460654	1.3309163	1.3147211	1.2974054	1.2788594	1.2589341	
1.2374258	1.2140512	1.1884165	1.1599541	1.1278266	1.0907173	1.0464109	0.9616390	0.8187643	0.5745132	
0.0030189	1.2708390	1.2708390	1.2693518	1.2669766	1.2636840	1.2594956	1.2544310	1.2485200	1.2417889	1.2342691
1.2259972	1.2170089	1.2073404	1.1970443	1.1861688	1.1747807	1.1629802	1.1508989	1.1387509	1.1268586	
1.1157531	1.1062765	1.0997820	1.0984880	1.1060476	1.1285460	1.1731845	1.0726243	0.9003707	0.8336806	
0.0030000	1.2230701	1.2230700	1.2218362	1.2199414	1.2173337	1.2140238	1.2100351	1.2054002	1.2001562	
1.1943424	1.1980064	1.1912079	1.1739957	1.1664426	1.1596237	1.1506176	1.1425352	1.1344993	1.1265470	1.1191368
1.1121595	1.1058742	1.1003476	1.0954249	1.0904026	1.0833615	1.0697509	1.0427028	1.0129136	0.9948704	
0.0030000	1.1942108	1.1842108	1.1834228	1.1819506	1.1798984	1.1773002	1.1741877	1.1706007	1.1665905	
1.1622075	1.1575127	1.1525571	1.1474150	1.1421478	1.1368239	1.1315125	1.1262691	1.1211473	1.1161975	
1.1114293	1.1068499	1.1024010	1.0979480	1.0932684	1.0880309	1.0818356	1.0743856	1.0659897	1.0583035	1.0531819
0.0030000	1.1527835	1.1527836	1.1522311	1.1511022	1.1494339	1.1472976	1.1447495	1.1418569	1.1386859	
1.1353039	1.1317950	1.1282194	1.1246699	1.1212146	1.1179113	1.1148101	1.1119479	1.1093456	1.1070013	
1.1046824	1.1029416	1.1010969	1.0992491	1.0973012	1.0951746	1.0928249	1.0903102	1.0878307	1.0857127	
1.0843146	0.0000003	1.1290234	1.1290234	1.1279231	1.1266077	1.1248636	1.1226928	1.1201632	1.1173582	1.1143780
1.1113322	1.1083394	1.1055098	1.1029577	1.1007929	1.0990870	1.0979033	1.0972750	1.0971963	1.0976398	
1.0935339	1.0997665	1.1012042	1.1026937	1.1041021	1.1053216	1.1062860	1.1069727	1.1074054	1.1076450	
1.1077613	0.0000003	1.1113244	1.1113244	1.1108035	1.1090052	1.1065304	1.1034995	1.1000204	1.0962284	
1.0922897	1.0883963	1.0847491	1.0815638	1.0790479	1.0773814	1.0767090	1.0771370	1.0787308	1.0814869	1.0853225
1.0900766	1.0955013	1.1012840	1.1070307	1.1126119	1.1176097	1.1219245	1.1254501	1.1281598	1.1300582	
1.1311758	0.0000003	1.1031473	1.1031473	1.1025792	1.1002672	1.0965139	1.0916126	1.0857832	1.0792601	
1.0723318	1.0653930	1.0589151	1.0530984	1.0486853	1.0459602	1.0452187	1.0466909	1.0505372	1.0568076	
1.0654060	1.0760272	1.0880566	1.1006516	1.1129534	1.1242771	1.1341810	1.1424506	1.1490405	1.1539984	1.1574273
1.1534069	0.0000003	1.1142159	1.1142159	1.1113822	1.1073273	1.1013258	1.0932624	1.0831755	1.0712177	
1.0577202	1.0432768	1.0288250	1.0156959	1.0049134	0.9976622	0.9943543	0.9953857	1.0011959	1.0122573	
1.0238543	1.0506469	1.0757971	1.1013108	1.1246490	1.1445034	1.1605805	1.1730945	1.1824834	1.1892223	
1.1936938	1.1962336	0.0000030	1.1498487	1.1498487	1.1469853	1.1415040	1.1334342	1.1222047	1.1071384	1.0874939
1.0625869	1.0321908	0.9974039	0.9623060	0.9336122	0.9141794	0.9028546	0.8993519	0.9048650	0.9221041	
0.9544805	1.0049075	1.0644829	1.1176062	1.1582106	1.1873472	1.2076998	1.2216985	1.2311888	1.2374657	
1.2413979	1.2435263	0.0000030	1.2114096	1.2114096	1.2114155	1.2085307	1.2032092	1.1949188	1.1823881	
1.1633334	1.1737137	1.0863205	1.0054684	0.8849950	0.7902928	0.7483137	0.7219319	0.7033951	0.6983534	0.7205707
0.7879730	0.9442774	1.1146879	1.2075931	1.2523288	1.2749231	1.2965841	1.2926400	1.2957525	1.2973052	
1.2980319	1.2983292	0.0000030	1.2866479	1.2866479	1.2898338	1.2927121	1.2959164	1.3000500	1.3059156	
1.3142234	1.3268566	1.3463402	1.3771641	0.8975745	0.3896543	0.3279743	0.3070248	0.2842963	0.2729265	
1.2904785	0.3768772	1.0165805	1.5222681	1.4619160	1.4240682	1.3992548	1.3824224	1.3707459	1.3625842	1.3569659
1.3532960	1.3512219	0.0003000	1.3472176	1.3472176	1.3515747	1.3565600	1.3629067	1.3711959	1.3821489	
1.3967520	1.4164275	1.4431775	1.4798968	1.0484922	0.3228217	0.0378934	0.0408711	0.0393838	0.0342552	
0.0197931	0.3508821	1.1489914	1.5674912	1.5163738	1.4792347	1.4520884	1.4321397	1.4174718	1.4067948	
1.3932357	1.3942164	1.3913572	0.0000000	1.3825226	1.3825226	1.3867819	1.3910705	1.3960898	1.4020979	1.4092028
1.4173859	1.4264488	1.4359312	1.4442670	0.9935976	0.3025085	0.0465074	0.0434403	0.0408912	0.0385936	
0.0370445	0.3221169	1.0629795	1.5026414	1.4881116	1.4729816	1.4590245	1.4469445	1.4369404	1.4283856	
1.4229918	1.4188272	1.4163810	0.0000300	1.3981074	1.3981074	1.4018142	1.4051563	1.4085990	1.4122368	
1.4161825	1.4201194	1.4239203	1.4268905	1.4288282	0.9795160	0.2976760	0.0468582	0.0442009	0.0418371	0.0397705
0.0330243	0.3147304	1.0407037	1.4778566	1.4719868	1.4649487	1.4575815	1.4505053	1.4441264	1.4387053	
1.4344084	1.4313139	1.4294541	0.0000000	1.4009064	1.4009064	1.4041340	1.4070642	1.4099610	1.4129780	
1.4157617	1.4184666	1.4207757	1.4224321	1.4231795	0.9751367	0.2961941	0.0466993	0.0442277	0.0419426	
0.0398509	0.0379138	0.3130436	1.0358238	1.4719743	1.4677811	1.4626378	1.4570558	1.4514983	1.4463222	1.4418089
1.4381534	1.4354919	1.4339636	0.0000000	1.3932359	1.3932359	1.3965482	1.3997823	1.4032590	1.4070070	
1.4109534	1.4149332	1.4186638	1.4217675	1.4237320	0.9759974	0.2965227	0.0465920	0.0439921	0.0416851	
0.0335699	0.0379769	0.3149192	1.0414201	1.4789093	1.4730865	1.4661008	1.4587879	1.4517605	1.4454257	

1 4400470	1 4357905	1 4327133	1 4308703	0 0000000	1 3724315	1 3724315	1 3763593	1 3805592	1 3955975	1 3916314
1 3987744	1 4069974	1 4161092	1 4255345	1 4340210	0 9865068	0 3001906	0 0459999	0 0420322	0 0406069	
0 0394545	0 0370524	0 3225043	1 0642992	1 5046275	1 4902449	1 4752626	1 4614403	1 4494735	1 4395666	
1 4316952	1 4257562	1 4216340	1 4192247	0 0000000	1 3322270	1 3322270	1 3364476	*1 3412839*	1 3475353	
1 3557893	*1 3667463*	1 3913794	1 4010543	*1 4277601*	1 4643461	1 0374802	*0 3191739*	0 0371053	0 0401182	*0 0398402*
0 0339866	0 0188291	*0 3513977*	1 1507308	1 5704280	*1 5195990*	1 4826965	1 4557457	*1 4359635*	1 4214420	
1 4108831	*1 4034123*	1 3984621	1 3956469	0 0000000	1 2677974	1 2677974	1 2704766	1 2730920	1 2762737	
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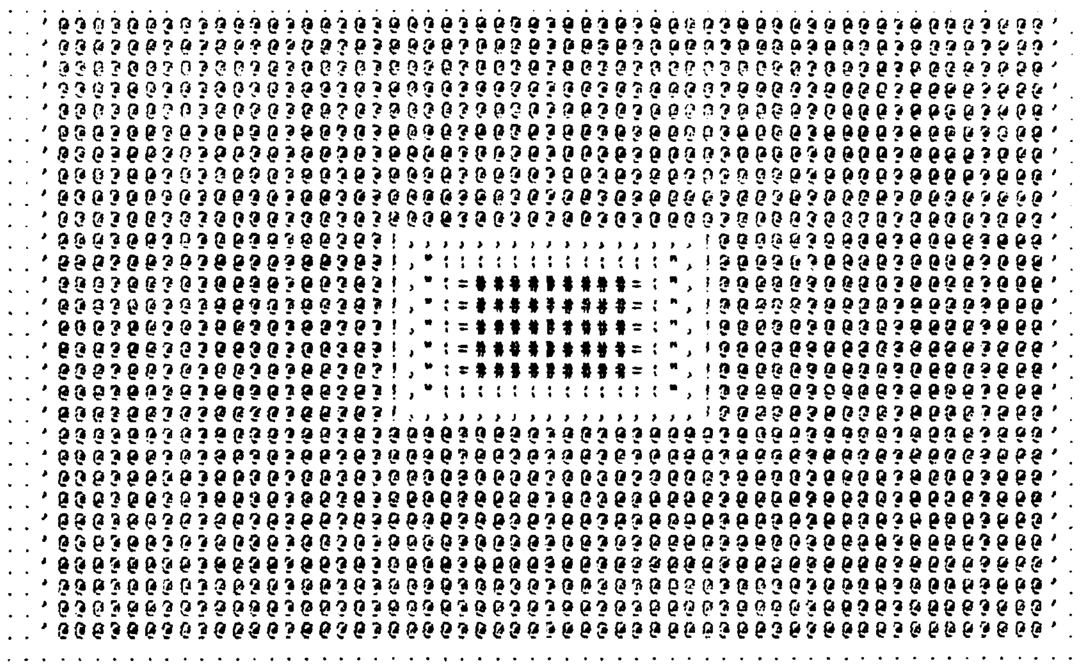

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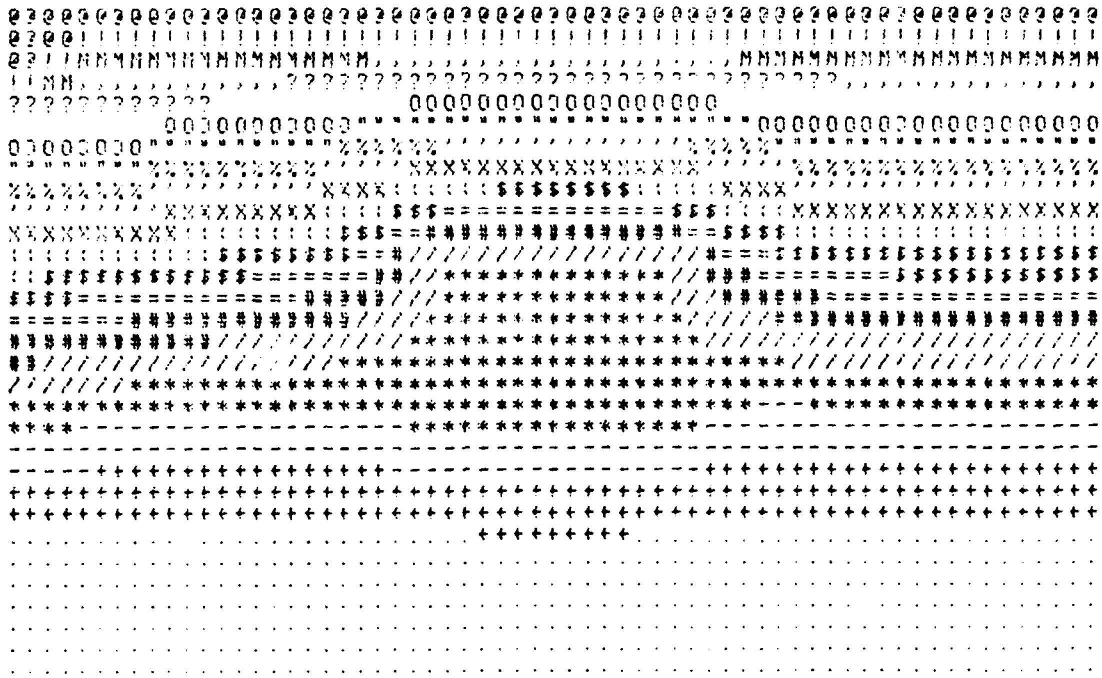
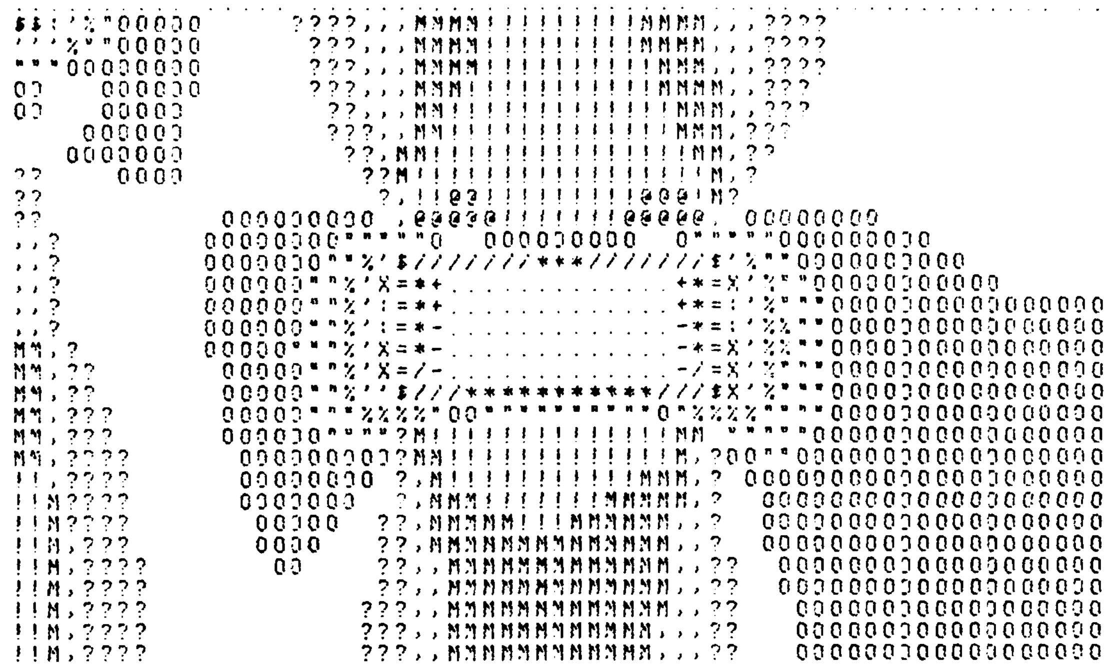
DISTRIBUTION DES LIGNES DE COURANT



MINIMUM = 0.00000E-01 MAXIMUM = 5.52470E-01 CLASSES = 2.762

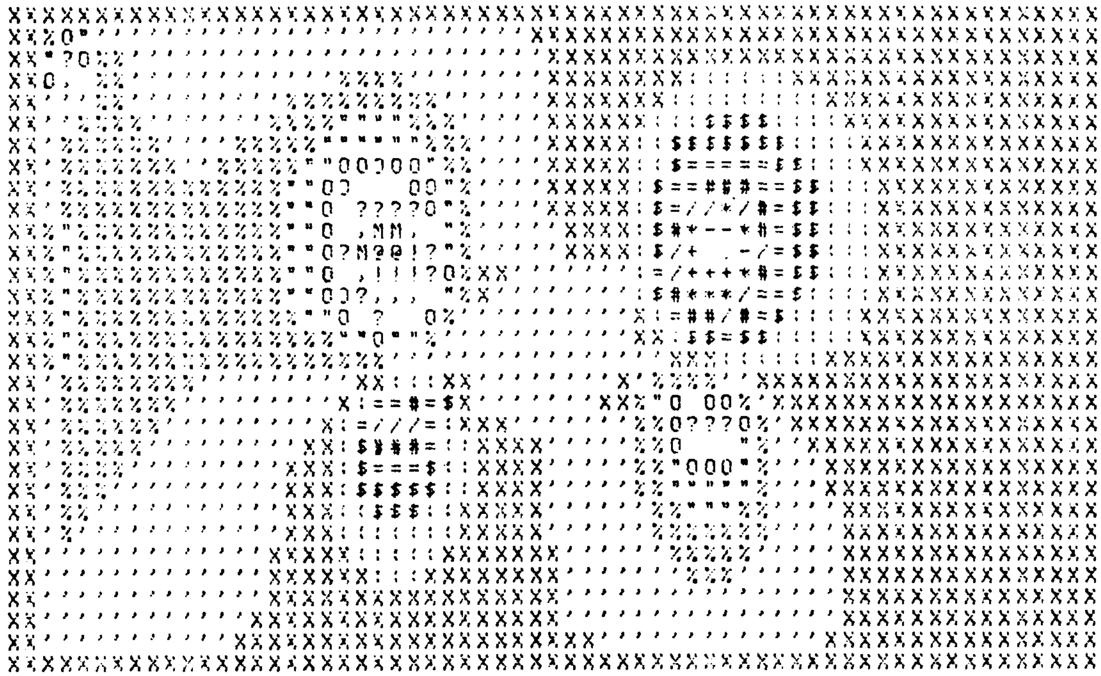
.	.LT.	2.762E-02	'	.LT.	3.039E-01
+	.LT.	5.525E-02	%	.LT.	3.315E-01
-	.LT.	8.287E-02	"	.LT.	3.591E-01
*	.LT.	1.105E-01	0	.LT.	3.867E-01
/	.LT.	1.381E-01		.LT.	4.144E-01
#	.LT.	1.657E-01	?	.LT.	4.420E-01
=	.LT.	1.934E-01	,	.LT.	4.696E-01
$	.LT.	2.210E-01	M	.LT.	4.972E-01
:	.LT.	2.486E-01	!	.LT.	5.248E-01
X	.LT.	2.762E-01	@	.LT.	5.525E-01



MINIMUM = 0.00000E-01 MAXIMUM = 1.57043E+00 CLASSES = 7.85

.	.LT.	7.852E-02	'	.LT.	8.637E-01
+	.LT.	1.570E-01	%	.LT.	9.423E-01
-	.LT.	2.356E-01	"	.LT.	1.021E+00
*	.LT.	3.141E-01	0	.LT.	1.099E+00
/	.LT.	3.926E-01		.LT.	1.178E+00
#	.LT.	4.711E-01	?	.LT.	1.256E+00
=	.LT.	5.496E-01	,	.LT.	1.335E+00
$	.LT.	6.282E-01	M	.LT.	1.413E+00
:	.LT.	7.067E-01	!	.LT.	1.492E+00
X	.LT.	7.852E-01	@	.LT.	1.570E+00

ISOVITESSE RADIALE



MINIMUM = -7.11170E-01 MAXIMUM = 7.18834E-01 CLASSES = 7.150

.	.LT.	-6.397E-01	'	.LT.	7.533E-02
+	.LT.	-5.682E-01	%	.LT.	1.468E-01
-	.LT.	-4.967E-01	"	.LT.	2.183E-01
*	.LT.	-4.252E-01	0	.LT.	2.898E-01
/	.LT.	-3.537E-01		.LT.	3.613E-01
#	.LT.	-2.822E-01	?	.LT.	4.328E-01
=	.LT.	-2.107E-01	,	.LT.	5.043E-01
$	.LT.	-1.392E-01	M	.LT.	5.758E-01
:	.LT.	-6.767E-02	!	.LT.	6.473E-01
X	.LT.	3.832E-03	@	.LT.	7.188E-01

STOP
%EOD

```
      DEFINE FILE 10=U:1(R:5084,G:1,BN,FI,RW)
      DEFINE FILE 5=105=M:SI
      DEFINE FILE 8=108=M:LO
      COMMON/DPRH/DP,RT,HT
      COMMON/FLUIDE/DENS,VIS,RE,PR
      COMMON/HEAT/TKG,TKS,QP,TA,TO
      COMMON/WALL/RHGW,QWG,RHSW,QWS
      COMMON/NTOT/MMAX,NMAX
      COMMON/TCALV/NF,NG,WS,TEST
      COMMON/DATPOR/PMINA0,PMAXA0,PMINA1,PMAXA1
      COMMON/INDPOR/I11A0,I22A0,J11A0,J4A0,I11A1,I22A1,J11A1,J4A1
      COMMON/IND/I,J
      COMMON/POROUS/POR,PORX,PORR
      COMMON/INSP/DR,DX,DR2,DX2,DRDR,DXDX,DXDR
      COMMON/BLKK/A1(41),B1(41),C1(41),D1(41),E1(41)
      COMMON/BLKE/A2(41),B2(41),C2(41),D2(41),E2(41)
      DIMENSION W1(31,31),W2(31,31),SOLN1(31),SOLN2(31),P(31,31)
C
      CALL LECRIB
C
      READ (5,600) J99MAX,EPS,Z1,PNSO,ALPHA,BETA
  600 FORMAT  (I5,5(F10.4))
      WRITE (8,700) J99MAX,EPS,Z1,RNSO,ALPHA,BETA
  700 FORMAT (5X,8HJ99MAX= ,I3,2X,                   5HEPS= ,F6.4,2X,4HZ1= ,
     1 E10.4,2X,6HRNSO= ,E10.4,2X,7HALPHA= ,F4.2,2X,6HBETA= ,F4.2,//)
      READ (10'1) P
C
C INITIALIZATION OF TEMPERATURES
C
      DO 5 I=1,MMAX
      DO 5 J=1,NMAX
      W1(I,J)=ALPHA
      W2(I,J)=BETA
    5 CONTINUE
      TKR=TKS/TKS
      M1=MMAX-1
      N1=NMAX-1
      DX=1./FLOAT(M1)
      DR=1./FLOAT(N1)
      J99=0
      G=FLOAT(M1-1)*FLOAT(N1-1)
C
C DETERMINATION OF COEFFICIENTS IN DISCRETIZED EQUATIONS
C
    7 J99=J99+1
      DT1=0.
      DT2=0.
      DEP1=0.
      DER2=0.
      EXA=0.
      ERA=0.
C
      DO 10 I=2,N1
      IP1=I+1
      IM1=I-1
      IP2=I+2
      IM2=I-2
      DO 20 J=2,N1
      JP1=J+1
      JM1=J-1
      JP2=J+2
      JM2=J-2
C
```

```
C FIND E(R)
C
      CALL SQUEL
C
      R= FLOAT(J-1)*DR
C
      US=(P(I,JP1)-P(I,JM1))/(2.*DR*R)
      VS=-(P(IP1,J)-P(IM1,J))*RT/(2.*DX*R*HT)
      VR=SQRT(US*US+VS*VS)
      REB=RE*DP*VR/RT
C
C THE DETERMINATION OF THE EDDY DIFFUSIVITY,E, AND ITS DERIVATIVES
C  USING A MIXING LENGTH MODEL
C
      VSU=0.
      VSL=0.
      USL=US
      USR=0.
      IF (I .EQ. M1) GO TO 50
      VSU=-RT*(P(IP2,J)-P(I,J))/(2.*DX*R*HT)
   50 IF (I .EQ. 2) GO TO 52
      VSL=-RT*(P(I,J)-P(IM2,J))/(2.*DX*R*HT)
   52 IF (J .EQ. 2) GO TO 54
      USL=(P(I,J)-P(I,JM2))/(2.*DR*R)
   54 IF (J .EQ. N1) GO TO 56
      USR=(P(I,JP2)-P(I,J))/(2.*DR*R)
   56 CONTINUE
      DVSX=(VSU-VSL)/(2.*DX)
      DUSR=(USR-USL)/(2.*DR)
      DDVSX=(VSU-2.*VS+VSL)/(DX*DX)
      DDUSR=(USR-2.*US+USL)/(DR*DR)
      Z2=1.
      Z3=1.
      IF (DVSX .LT. 0.) Z2=-1.
      IF (DUSR .LT. 0.)  Z3=-1.
C
      EX=Z1*DP*DP*RE*VIS*ABS(DVSX)/(RT*HT)
      ER=Z1*DP*DP*RE*VIS*ABS(DUSR)/(RT*RT)
      EXX=Z1*Z2*DP*DP*RE*VIS*DDVSX/(RT*HT)
      ERR=Z1*Z3*DP*DP*RE*VIS*DDUSR/(RT*RT)
      EXA=EXA+EX/G
      ERA=ERA+ER/G
C
C FIND NU(RE,E(R))
C
      C=1.-POR
      O2=C**0.33333
      O1=2.-3.*O2+3.*O2**5.-2.*O2**6.
      PNU=1.6*((REB*PR/(POR*O1))*(1.-C**1.66667))**0.33333
C
C CALCULATE COEFFICIENTS IN EQUATIONS
C
      AA1=RT*(POR+PR*EX/VIS)/(RE*PR*HT*HT)
      AA2=RT*(1.-POR)*TKR/(RE*PR*HT*HT)
      CC1=RT*(POR+PR*ER/VIS)/(RE*PR*RT*RT)
      CC2=RT*(1.-POR)*TKR/(RE*PR*RT*RT)
      H=6*(1.-POR)*PNU*RT/(RE*PR*DP*DP)
      Q=RT*QP*(1.-PMAXA0)/(RE*PR*TKG*TO)
      V1=-CC1/R-RT*(PORR+PR*ERR/VIS)/(RE*PR*RT*RT)+VS/RT
      V2=-CC2/R+RT*PORR*TKR/(RE*PR*RT*RT)
      U1=US/HT-RT*(PORX+PR*EXX/VIS)/(RE*PR*HT*HT)
      U2=RT*TKR*PORX/(RE*PR*HT*HT)
C
C COEFFICIENTS USED IN UPWIND DIFFERENCING
C
      IF (U1 .LT. 0.) GO TO 60
      A8=-1.
      B8=1.
      C8=0.
      GO TO 63
   60 A8=0.
      B8=-1.
      C8=1.
   63 IF (V1 .LT. 0.) GO TO 65
      A9=-1.
      B9=1.
      C9=0.
      GO TO 67
   65 A9=0.
      B9=-1.
```

```
      C9=1.
   67 CONTINUE
C
      A1(J)=-CC1/DR/DR+V1*A9/DR
      B1(J)=2.*(AA1/DX/DX+CC1/DR/DR)+H+U1*B8/DX+V1*B9/DR
      C1(J)=-CC1/DR/DR+V1*C9/DR
      D1(J)=H
      E1(J)=AA1*(W1(IP1,J)+W1(IM1,J))/DX/DX-U1*(A8*W1(IM1,J)+C8*W1(IP1,
     1 J))/DX
C
C USE CENTRAL DIFFERENCING FOR THETA X AND THETA R
C
      B8=0.
      B9=0.
      C8=0.5
      C9=0.5
      A8=-0.5
      A9=-0.5
C
      A2(J)=-CC2/DR/DR+V2*A9/DR
      B2(J)=2.*(AA2/DX/DX+CC2/DR/DR)+H+U2*B8/DX+V2*B9/DR
      C2(J)=-CC2/DR/DR+V2*C9/DR
      D2(J)=H
      E2(J)=AA2*(W2(IP1,J)+W2(IM1,J))/DX/DX-U2*(A8*W2(IM1,J)+C8*W2(IP1,
     1 J))/DX+Q
C
   (0 CONTINUE
C
C ADJUST COEFFICIENTS SO AS TO SATISFY BOUNDARY CONDITIONS
C
      B1(2)=B1(2)+A1(2)
      B2(2)=B2(2)+A2(2)
      B1(N1)=B1(N1)+C1(N1)/(1.+DR*RT*RNGW)
      E1(N1)=E1(N1)-C1(N1)*DR*RT*RNGW*TA/(TO*(1.+DR*RT*RNGW))
      B2(N1)=B2(N1)+C2(N1)/(1.+DR*RT*RNSW)
      E2(N1)=E2(N1)-C2(N1)*DR*RT*RNSW*TA/(TO*(1.+DR*RT*RNSW))
C
C EXECUTE SOLUTION TECHNIQUE TO SOLVE COUPLED TRIDIAGONAL SYSTEM
C
      CALL TRISBU (NMAX,SOLN1,SOLN2)
C
C EXECUTE RELAXATION TECHNIQUE IN ORDER TO UPDATE UNKNOWN VALUES
C
      DO 30 J=2,N1
C
      SN1=W1(I,J)+WS*(SOLN1(J)-W1(I,J))
      SN2=W2(I,J)+WS*(SOLN2(J)-W2(I,J))
C
      ERR1=ABS(SN1-SOLN1(J))
      ERR2=ABS(SN2-SOLN2(J))
      DT1=DT1+ERR1/G
      DT2=DT2+ERR2/G
C
C FIND MAXIMUM ERROR IN THE NET AND ITS POSITION
C
      CALL CONV2(I,J,ERR1,ERR2,LI1,LI2,LJ1,LJ2,DER1,DER2)
C
      W1(I,J)=SN1
      W2(I,J)=SN2
   30 CONTINUE
      W1(I,1)=W1(I,2)
      W2(I,1)=W2(I,2)
      W1(I,NMAX)=(W1(I,N1)+DR*RT*RNGW*TA/TO)/(1.+DR*RT*RNGW)
      W2(I,NMAX)=(W2(I,N1)+DR*RT*RNSW*TA/TO)/(1.+DR*RT*RNSW)
   10 CONTINUE
      DO 35 J=1,NMAX
      W1(MMAX,J)=W1(M1,J)
      W2(MMAX,J)=W2(M1,J)
      W1(1,J)=1.
      W2(1,J)=(DX*HT*RNSO+W2(2,J))/(1.+DX*HT*RNSO)
   35 CONTINUE
      IF (J99 .LE. 30) GO TO 38
      GO TO 39
   38 WRITE(103,300) J99,LI1,LJ1,DER1,LI2,LJ2,DER2
  300 FORMAT(1X,2HK=, I3,3H X=, I2,3H R=, I2, 9H ERRMAX1=, E12.6,
     1 2X,2HX=, I2,3H R=, I2, 9H ERRMAX2=, E12.6,/)
      WRITE(103,400) DT1,DT2
  400 FORMAT(1X,9HERRAVG1=, E12.6,10H  ERRAVG2=, E12.6,/)
   39 CONTINUE
      IF (J99 .GT. J99MAX) GO TO 40
```

```
      IF (DT1 .GT. EPS) GO TO 7
      IF (DT2 .GT. EPS) GO TO 7
   40 CONTINUE
      IF (J99 .LE. 30) GO TO 45
      WRITE(108,300) J99,LI1,LJ1,DER1,LI2,LJ2,DER2
      WRITE(108,400) DT1,DT2
   45 CONTINUE
      EF=SQRT(EXA*EXA+ERA*ERA)
      WRITE (108,425) EF
  425 FORMAT (1X,13HEFFECTIVE E= ,E10.4,/)
C
C THE SOLUTION FOLLOWS
C
      WRITE (108,450)
 450  FORMAT(/,1X,47HTEMPERATURE DISTRIBUTIONS FOR THE GAS AND SOLID,//)
      DO 55 K=1,MMAX
      L=MMAX-K+1
      WRITE (108,500) (W1(L,J),J=1,NMAX)
      WRITE (108,800) (W2(L,J),J=1,NMAX)
  500 FORMAT (2X,11F9.4,/)
  800 FORMAT (1X,1H*,11F9.4,//)
   55 CONTINUE
C
      WRITE (10'3) W1
      WRITE (10'4) W2
C
      END
LES
```

```
**

 FR,CL,SL,UL,(HOTBEV)

503

IPLANTATION DES SEGMENTS***
    0000
    1B34
      96
    5DAC
    5DCA
    5E22
    5E56
    5E60
    5E72
    5E82
    5EC2
    5F34
    5F38
    5F62
    5FA4
    6598
    659C
    65A2
    65BH
    6644
    6648
    6654
    6658
    665E
    6662
    6666
    666C
    669E
    6724
    6B6A
    6B6E
```

46

```
DP= 0.0050000      RT= 0.0500000      HT= 0.1000000
DENS=  .1211E+01      VISCO=  .1530E-04      RET= 4000.00      PR=  0.72
GK=   0.02500      SK=   0.75000      Q= 399999.98
TEX= 20.0      T0=15.00
M=   31      N=   31      NF=  100      NG=   20
OVER RELAXATION FACTOR= 1.05      TEST=       0.01
NUWG = *******      QWG =       0.00
NUWS = *******      QWS =       0.00
        BLOKAGE 1*
PMINA0 =    0.100   PMAXA0 =    0.400
I11A0 =  11  I22A0 =  21  J11A0 =  11  J4A0 =  21

        BLOKAGE 2*
PMINA1 =    0.100   PMAXA1 =    0.400
I11A1 =  50  I22A1 =  50  J11A1 =  50  J4A1 =  50

   J99MAX= 200  EPS= 0.0001  Z1=   .1427E+00  RHSO=   .0000E+00  ALPHA= 1.00  BETA= 1.00

K=  1 X=30 R=26 ERRMAX1= .261211E-01  X=30 R=26 ERRMAX2= .245571E-01
ERRAVG1= .137386E-01  ERRAVG2= .149187E-01
K=  2 X=20 R=15 ERRMAX1= .124416E-01  X=30 R=14 ERRMAX2= .143375E-01
ERRAVG1= .498161E-02  ERRAVG2= .698663E-02
K=  3 X=19 R=15 ERRMAX1= .926781E-02  X=30 R=14 ERRMAX2= .963020E-02
ERRAVG1= .311554E-02  ERRAVG2= .385653E-02
K=  4 X=18 R=16 ERRMAX1= .661278E-02  X=18 R=16 ERRMAX2= .660515E-02
ERRAVG1= .170721E-02  ERRAVG2= .214579E-02
K=  5 X=18 R=16 ERRMAX1= .450993E-02  X=18 R=16 ERRMAX2= .450230E-02
ERRAVG1= .101622E-02  ERRAVG2= .124753E-02
 =  6 X=18 R=16 ERRMAX1= .299358E-02  X=18 R=15 ERRMAX2= .300026E-02
ERRAVG1= .611704E-03  ERRAVG2= .743903E-03
K=  7 X=18 R=15 ERRMAX1= .195599E-02  X=18 R=15 ERRMAX2= .196648E-02
ERRAVG1= .376413E-03  ERRAVG2= .453393E-03
K=  8 X=18 R=15 ERRMAX1= .126934E-02  X=18 R=15 ERRMAX2= .127602E-02
ERRAVG1= .234520E-03  ERRAVG2= .280629E-03
K=  9 X=18 R=15 ERRMAX1= .819206E-03  X=18 R=15 ERRMAX2= .823021E-03
ERRAVG1= .147451E-03  ERRAVG2= .175611E-03
K= 10 X=18 R=15 ERRMAX1= .526428E-03  X=18 R=15 ERRMAX2= .529289E-03
ERRAVG1= .932289E-04  ERRAVG2= .110667E-03
K= 11 X=18 R=15 ERRMAX1= .337601E-03  X=18 R=15 ERRMAX2= .339508E-03
ERRAVG1= .592476E-04  ERRAVG2= .701482E-04
EFFECTIVE E=  .4695E-03

TEMPERATURE DISTRIBUTIONS FOR THE GAS AND SOLID
```

47

	2.0104	2.0104	2.0119	2.0164	2.0255	2.0402	2.0610	2.0884	2.1216	2.1584	2.1949
	2.2252	2.2430	2.2432	2.2235	2.1870	2.1412	2.0933	2.0477	2.0059	1.9682	1.9339
	1.9023	1.8712	1.8375	1.7971	1.7447	1.6726	1.5680	1.3945	1.3333		
*	2.1184	2.1184	2.1213	2.1275	2.1380	2.1536	2.1747	2.2012	2.2318	2.2644	2.2952
*	2.3194	2.3322	2.3300	2.3117	2.2799	2.2394	2.1956	2.1524	2.1115	2.0737	2.0385
*	2.0048	1.9703	1.9320	1.8855	1.8251	1.7437	1.6333	1.4883	1.3333		
	2.0104	2.0104	2.0119	2.0164	2.0255	2.0402	2.0610	2.0884	2.1216	2.1584	2.1949
	2.2252	2.2430	2.2432	2.2235	2.1870	2.1412	2.0933	2.0477	2.0059	1.9682	1.9339
	1.9023	1.8712	1.8375	1.7971	1.7447	1.6726	1.5680	1.3945	1.3333		
*	2.1184	2.1184	2.1213	2.1275	2.1380	2.1536	2.1747	2.2012	2.2318	2.2644	2.2952
*	2.3194	2.3322	2.3300	2.3117	2.2799	2.2394	2.1956	2.1524	2.1115	2.0737	2.0385
*	2.0048	1.9703	1.9320	1.8855	1.8251	1.7437	1.6333	1.4883	1.3333		
	1.9703	1.9703	1.9717	1.9764	1.9855	2.0004	2.0218	2.0503	2.0854	2.1252	2.1653
	2.1993	2.2201	2.2216	2.2009	2.1617	2.1129	2.0631	2.0165	1.9744	1.9367	1.9029
	1.8721	1.8424	1.8106	1.7728	1.7235	1.6555	1.5564	1.3916	1.3333		
*	2.0856	2.0856	2.0885	2.0948	2.1054	2.1213	2.1430	2.1705	2.2029	2.2377	2.2711
*	2.2978	2.3125	2.3111	2.2923	2.2589	2.2166	2.1714	2.1273	2.0861	2.0483	2.0135
*	1.9805	1.9472	1.9105	1.8661	1.8085	1.7306	1.6245	1.4846	1.3333		
	1.9278	1.9278	1.9293	1.9339	1.9430	1.9579	1.9797	2.0091	2.0462	2.0892	2.1336
	2.1719	2.1963	2.1998	2.1782	2.1356	2.0835	2.0314	1.9838	1.9414	1.9038	1.8703
	1.8404	1.8122	1.7824	1.7471	1.7012	1.6375	1.5442	1.3985	1.3333		
*	2.0450	2.0450	2.0479	2.0542	2.0650	2.0812	2.1035	2.1322	2.1665	2.2042	2.2410
*	2.2711	2.2885	2.2984	2.2691	2.2336	2.1889	2.1419	2.0966	2.0550	2.0172	1.9828
*	1.9507	1.9189	1.8841	1.8424	1.7881	1.7146	1.6138	1.4801	1.3333		
	1.8848	1.8848	1.8962	1.8907	1.8996	1.9144	1.9362	1.9663	2.0051	2.0514	2.1006
	2.1439	2.1729	2.1791	2.1567	2.1102	2.0541	1.9997	1.9511	1.9084	1.8708	1.8376
	1.8085	1.7817	1.7539	1.7213	1.6787	1.6193	1.5317	1.3953	1.3333		
*	2.0025	2.0025	2.0054	2.0117	2.0224	2.0387	2.0615	2.0912	2.1276	2.1683	2.2091
*	2.2432	2.2640	2.2657	2.2459	2.2081	2.1607	2.1115	2.0651	2.0229	1.9850	1.9509
*	1.9197	1.8894	1.8567	1.8177	1.7670	1.6979	1.6026	1.4752	1.3333		
	1.8417	1.8417	1.8430	1.8473	1.8559	1.8702	1.8917	1.9220	1.9622	2.0119	2.0665
	2.1154	2.1499	2.1601	2.1374	2.0860	2.0253	1.9683	1.9188	1.8759	1.8382	1.8050
	1.7767	1.7513	1.7256	1.6956	1.6565	1.6013	1.5193	1.3922	1.3333		
*	1.9597	1.9597	1.9625	1.9686	1.9792	1.9953	2.0183	2.0489	2.0870	2.1310	2.1761
*	2.2149	2.2398	2.2440	2.2240	2.1836	2.1331	2.0816	2.0339	1.9911	1.9531	1.9192
*	1.8838	1.8598	1.8293	1.7930	1.7458	1.6812	1.5913	1.4704	1.3333		
	1.7987	1.7987	1.8000	1.8040	1.8121	1.8257	1.8465	1.8764	1.9175	1.9703	2.0310
	2.0860	2.1270	2.1431	2.1209	2.0635	1.9974	1.9377	1.8873	1.8443	1.8064	1.7730
	1.7453	1.7213	1.6977	1.6704	1.6347	1.5838	1.5072	1.3791	1.3333		
*	1.9167	1.9167	1.9195	1.9254	1.9356	1.9514	1.9743	2.0053	2.0451	2.0923	2.1422

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*	2.1862	2.2161	2.2240	2.2043	2.1609	2.1068	2.0528	2.0037	1.9603	1.9219	1.8880
*	1.8582	1.8306	1.8021	1.7696	1.7250	1.6647	1.5802	1.4656	1.3333		
	1.7562	1.7562	1.7573	1.7610	1.7685	1.7812	1.8010	1.8300	1.8710	1.9265	1.9944
	2.0550	2.1034	2.1283	2.1087	2.0435	1.9708	1.9082	1.8572	1.8143	1.7761	1.7419
	1.7146	1.6919	1.6704	1.6460	1.6138	1.5672	1.4959	1.3763	1.3333		
*	1.8740	1.8740	1.8765	1.8822	1.8920	1.9073	1.9298	1.9610	2.0020	2.0524	2.1076
*	2.1571	2.1929	2.2059	2.1877	2.1409	2.0827	2.0259	1.9754	1.9312	1.8922	1.8579
*	1.8223	1.8019	1.7754	1.7447	1.7047	1.6488	1.5696	1.4609	1.3333		
	1.7143	1.7143	1.7154	1.7187	1.7256	1.7374	1.7560	1.7838	1.8240	1.8812	1.9577
	2.0224	2.0781	2.1154	2.1026	2.0272	1.9466	1.8810	1.8297	1.7872	1.7486	1.7124
	1.6849	1.6635	1.6440	1.6226	1.5941	1.5521	1.4859	1.3737	1.3333		
*	1.8314	1.8314	1.8338	1.8392	1.8485	1.8633	1.8853	1.9165	1.9596	2.0120	2.0729
*	2.1279	2.1703	2.1903	2.1753	2.1251	2.0622	2.0023	1.9501	1.9049	1.8649	1.8293
*	1.7935	1.7739	1.7493	1.7215	1.6852	1.6338	1.5597	1.4565	1.3333		
	1.6736	1.6736	1.6745	1.6776	1.6840	1.6951	1.7128	1.7395	1.7789	1.8372	1.9251
	1.9835	2.0498	2.1028	2.1055	2.0166	1.9267	1.8580	1.8068	1.7658	1.7268	1.6856
	1.6569	1.6363	1.6198	1.6004	1.5759	1.5386	1.4776	1.3716	1.3333		
*	1.7892	1.7892	1.7915	1.7966	1.8055	1.8199	1.8416	1.8730	1.9164	1.9734	2.0408
*	2.1002	2.1486	2.1775	2.1690	2.1157	2.0479	1.9844	1.9301	1.8836	1.8417	1.8031
*	1.7719	1.7468	1.7240	1.6992	1.6667	1.6199	1.5507	1.4525	1.3333		
	1.6345	1.6345	1.6354	1.6332	1.6442	1.6548	1.6720	1.6986	1.7390	1.8006	1.9100
	1.9645	2.0210	2.0360	2.1203	2.0161	1.9164	1.8443	1.7939	1.7564	1.7182	1.6628
	1.6308	1.6104	1.5946	1.5793	1.5588	1.5265	1.4709	1.3698	1.3333		
*	1.7480	1.7480	1.7501	1.7549	1.7634	1.7775	1.7991	1.8312	1.8771	1.9395	2.0160
*	2.0770	2.1287	2.1665	2.1695	2.1155	2.0432	1.9752	1.9180	1.8699	1.8256	1.7803
	1.7458	1.7204	1.6992	1.6774	1.6490	1.6068	1.5426	1.4488	1.3333		
	1.5976	1.5976	1.5994	1.6011	1.6067	1.6169	1.6340	1.6618	1.7072	1.7838	1.9249
	1.9695	2.0029	2.0662	2.1427	2.0433	1.9401	1.8603	1.8087	1.7800	1.7412	1.6419
	1.6060	1.5855	1.5714	1.5597	1.5421	1.5148	1.4649	1.3683	1.3333		
*	1.7087	1.7087	1.7107	1.7151	1.7232	1.7368	1.7585	1.7921	1.8421	1.9128	1.9996
*	2.0553	2.1016	2.1461	2.1656	2.1188	2.0448	1.9708	1.9108	1.8655	1.8214	1.7617
*	1.7217	1.6952	1.6754	1.6562	1.6317	1.59[illegible]2	1.5349	1.4454	1.3333		
	1.5632	1.5632	1.5640	1.5665	1.5718	1.5814	1.5978	1.6253	1.6716	1.7524	1.9019
	1.9631	2.0050	2.0557	2.1425	2.0980	2.0029	1.8922	1.8380	1.7984	1.7411	1.6281
	1.5846	1.5619	1.5482	1.5373	1.5242	1.5019	1.4583	1.3665	1.3333		
*	1.6722	1.6722	1.6740	1.6791	1.6858	1.6989	1.7202	1.7539	1.8054	1.8799	1.9723
*	2.0317	2.0681	2.1178	2.1528	2.1260	2.0559	1.9706	1.9056	1.8676	1.8162	1.7473
*	1.7012	1.6722	1.6525	1.6353	1.6141	1.5812	1.5270	1.4420	1.3333		
	1.5306	1.5306	1.5313	1.5335	1.5383	1.5468	1.5615	1.5862	1.6286	1.7044	1.8522

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	1.9216	1.9747	2.0421	2.1321	2.1291	2.0747	1.9227	1.8398	1.7844	1.7183	1.6056
	1.5592	1.5362	1.5234	1.5145	1.5045	1.4871	1.4500	1.3644	1.3333		
*	1.6381	1.6381	1.6397	1.6434	1.6504	1.6624	1.6821	1.7137	1.7629	1.8355	1.9286
*	1.9929	2.0355	2.0970	2.1361	2.1314	2.0774	1.9801	1.9058	1.8569	1.7979	1.7257
*	1.6772	1.6476	1.6287	1.6134	1.5954	1.5670	1.5181	1.4382	1.3333		
	1.4993	1.4993	1.4999	1.5018	1.5058	1.5130	1.5255	1.5467	1.5834	1.6505	1.7863
	1.9562	1.9120	1.9856	2.0867	2.0921	2.0440	1.8872	1.7993	1.7419	1.6770	1.5725
	1.5295	1.5086	1.4974	1.4905	1.4834	1.4704	1.4399	1.3619	1.3333		
*	1.6058	1.6059	1.6072	1.6104	1.6165	1.6269	1.6442	1.6722	1.7164	1.7828	1.8700
*	1.9334	1.9782	2.0346	2.0923	2.0958	2.0469	1.9477	1.8706	1.8204	1.7623	1.6937
*	1.6479	1.6204	1.6033	1.5904	1.5756	1.5516	1.5083	1.4341	1.3333		
	1.4691	1.4691	1.4696	1.4711	1.4743	1.4803	1.4905	1.5079	1.5394	1.5954	1.7153
	1.7838	1.8403	1.9172	2.0232	2.0331	1.9890	1.8351	1.7480	1.6915	1.6299	1.5363
	1.4983	1.4801	1.4708	1.4657	1.4612	1.4523	1.4285	1.3590	1.3333		
*	1.5750	1.5750	1.5761	1.5788	1.5839	1.5925	1.6070	1.6307	1.6696	1.7267	1.8048
*	1.8647	1.9094	1.9682	2.0301	2.0379	1.9928	1.8963	1.8208	1.7727	1.7189	1.6569
*	1.6159	1.5915	1.5770	1.5665	1.5549	1.5352	1.4976	1.4295	1.3333		
	1.4398	1.4398	1.4401	1.4413	1.4439	1.4485	1.4566	1.4705	1.4949	1.5410	1.6410
	1.7054	1.7617	1.8385	1.9456	1.9579	1.9182	1.7726	1.6895	1.6359	1.5799	1.4997
	1.4670	1.4514	1.4440	1.4406	1.4382	1.4331	1.4157	1.3558	1.3333		
*	1.5453	1.5453	1.5462	1.5483	1.5522	1.5592	1.5709	1.5901	1.6212	1.6694	1.7357
*	1.7833	1.8319	1.8905	1.9536	1.9639	1.9233	1.8330	1.7620	1.7195	1.6715	1.6179
*	1.5827	1.5620	1.5501	1.5421	1.5334	1.5179	1.4861	1.4247	1.3333		
	1.4110	1.4110	1.4113	1.4122	1.4142	1.4178	1.4240	1.4347	1.4535	1.4890	1.5655
	1.6223	1.6744	1.7476	1.8519	1.8603	1.8244	1.6969	1.6238	1.5768	1.5285	1.4629
	1.4356	1.4223	1.4170	1.4151	1.4147	1.4130	1.4019	1.3524	1.3333		
	1.5165	1.5165	1.5172	1.5188	1.5218	1.5271	1.5361	1.5509	1.5749	1.6124	1.6646
*	1.7088	1.7462	1.8020	1.8623	1.8721	1.8368	1.7583	1.6959	1.6598	1.6216	1.5778
*	1.5490	1.5322	1.5230	1.5174	1.5115	1.5001	1.4740	1.4197	1.3333		
	1.3825	1.3825	1.3827	1.3834	1.3849	1.3877	1.3923	1.4002	1.4141	1.4399	1.4920
	1.5394	1.5868	1.6441	1.7195	1.7277	1.7109	1.6237	1.5635	1.5199	1.4776	1.4262
	1.4043	1.3941	1.3900	1.3892	1.3905	1.3918	1.3869	1.3488	1.3333		
*	1.4885	1.4885	1.4890	1.4902	1.4924	1.4963	1.5028	1.5134	1.5306	1.5573	1.5941
*	1.6275	1.6600	1.7148	1.7600	1.7667	1.7422	1.6848	1.6304	1.6008	1.5709	1.5372
*	1.5150	1.5024	1.4959	1.4925	1.4893	1.4817	1.4614	1.4144	1.3333		
	1.3536	1.3536	1.3538	1.3544	1.3556	1.3576	1.3609	1.3661	1.3749	1.3903	1.4189
	1.4440	1.4649	1.4784	1.4929	1.5066	1.5163	1.5129	1.4807	1.4510	1.4212	1.3880
	1.3725	1.3651	1.3626	1.3629	1.3655	1.3696	1.3707	1.3448	1.3333		
*	1.4609	1.4609	1.4613	1.4622	1.4638	1.4666	1.4710	1.4779	1.4886	1.5046	1.5261
*	1.5464	1.5736	1.5991	1.6174	1.6236	1.6175	1.5985	1.5686	1.5397	1.5181	1.4959

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*	1.4811	1.4729	1.4690	1.4676	1.4667	1.4627	1.4482	1.4090	1.3333		
	1.3237	1.3237	1.3239	1.3243	1.3252	1.3267	1.3288	1.3318	1.3359	1.3417	1.3502
	1.3520	1.3643	1.3676	1.3698	1.3700	1.3705	1.3695	1.3658	1.3591	1.3512	1.3436
	1.3378	1.3345	1.3341	1.3355	1.3394	1.3460	1.3531	1.3405	1.3333		
*	1.4328	1.4323	1.4332	1.4339	1.4353	1.4373	1.4404	1.4448	1.4509	1.4592	1.4698
*	1.4812	1.4927	1.5016	1.5068	1.5079	1.5047	1.4975	1.4968	1.4746	1.4637	1.4543
*	1.4475	1.4435	1.4421	1.4424	1.4436	1.4431	1.4343	1.4032	1.3333		
	1.2925	1.2925	1.2926	1.2930	1.2937	1.2948	1.2963	1.2983	1.3008	1.3038	1.3074
	1.3111	1.3127	1.3136	1.3141	1.3150	1.3158	1.3159	1.3152	1.3135	1.3102	1.3070
	1.3047	1.3036	1.3040	1.3065	1.3117	1.3207	1.3338	1.3357	1.3333		
*	1.4033	1.4033	1.4036	1.4043	1.4053	1.4069	1.4091	1.4120	1.4156	1.4200	1.4250
*	1.4299	1.4340	1.4368	1.4394	1.4390	1.4382	1.4360	1.4324	1.4279	1.4231	1.4188
*	1.4157	1.4141	1.4142	1.4160	1.4192	1.4222	1.4194	1.3969	1.3333		
	1.2596	1.2596	1.2597	1.2600	1.2605	1.2612	1.2622	1.2633	1.2647	1.2661	1.2676
	1.2689	1.2699	1.2707	1.2713	1.2720	1.2726	1.2730	1.2730	1.2727	1.2721	1.2714
	1.2711	1.2715	1.2730	1.2762	1.2824	1.2935	1.3125	1.3304	1.3333		
*	1.3716	1.3716	1.3719	1.3724	1.3731	1.3742	1.3756	1.3772	1.3792	1.3814	1.3836
*	1.3857	1.3873	1.3986	1.3895	1.3899	1.3899	1.3894	1.3984	1.3870	1.3854	1.3840
*	1.3872	1.3833	1.3948	1.3880	1.3931	1.3995	1.4030	1.3999	1.3333		
	1.2259	1.2259	1.2260	1.2262	1.2265	1.2269	1.2275	1.2282	1.2290	1.2298	1.2306
	1.2314	1.2322	1.2328	1.2335	1.2342	1.2348	1.2354	1.2358	1.2361	1.2364	1.2368
	1.2374	1.2386	1.2407	1.2444	1.2511	1.2637	1.2884	1.3244	1.3333		
*	1.3384	1.3384	1.3385	1.3388	1.3393	1.3400	1.3408	1.3418	1.3429	1.3440	1.3452
*	1.3463	1.3472	1.3480	1.3487	1.3493	1.3496	1.3498	1.3498	1.3497	1.3495	1.3496
*	1.3501	1.3513	1.3538	1.3581	1.3649	1.3745	1.3845	1.3820	1.3333		
	1.1920	1.1920	1.1921	1.1922	1.1924	1.1927	1.1931	1.1936	1.1941	1.1947	1.1953
	1.1959	1.1965	1.1972	1.1978	1.1985	1.1993	1.1999	1.2006	1.2012	1.2019	1.2027
	1.2037	1.2052	1.2075	1.2113	1.2180	1.2313	1.2608	1.3175	1.3333		
*	1.3043	1.3043	1.3044	1.3046	1.3050	1.3054	1.3059	1.3065	1.3072	1.3080	1.3087
*	1.3095	1.3102	1.3109	1.3116	1.3122	1.3128	1.3133	1.3138	1.3143	1.3148	1.3156
*	1.3167	1.3185	1.3215	1.3265	1.3347	1.3473	1.3638	1.3730	1.3333		
	1.1584	1.1584	1.1585	1.1585	1.1587	1.1589	1.1592	1.1596	1.1600	1.1605	1.1610
	1.1615	1.1621	1.1627	1.1633	1.1640	1.1648	1.1655	1.1663	1.1670	1.1678	1.1688
	1.1699	1.1715	1.1737	1.1772	1.1835	1.1962	1.2291	1.3094	1.3333		
*	1.2702	1.2702	1.2703	1.2705	1.2707	1.2710	1.2714	1.2718	1.2723	1.2729	1.2735
*	1.2742	1.2748	1.2755	1.2762	1.2769	1.2776	1.2783	1.2790	1.2798	1.2806	1.2817
*	1.2831	1.2851	1.2884	1.2937	1.3027	1.3177	1.3406	1.3627	1.3333		
	1.1254	1.1254	1.1254	1.1255	1.1256	1.1258	1.1260	1.1263	1.1266	1.1270	1.1275
	1.1280	1.1285	1.1291	1.1297	1.1303	1.1310	1.1317	1.1324	1.1332	1.1340	1.1350
	1.1361	1.1375	1.1395	1.1424	1.1476	1.1588	1.1926	1.2999	1.3333		
*	1.2365	1.2365	1.2365	1.2366	1.2368	1.2371	1.2374	1.2378	1.2382	1.2387	1.2392

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*  1.2399  1.2405  1.2411  1.2418  1.2425  1.2433  1.2441  1.2449  1.2457  1.2467  1.2479

*  1.2493  1.2514  1.2546  1.2599  1.2692  1.2859  1.3147  1.3510  1.3333
   1.0931  1.0931  1.0931  1.0932  1.0932  1.0934  1.0935  1.0938  1.0940  1.0943  1.0947

   1.0951  1.0956  1.0961  1.0966  1.0972  1.0978  1.0984  1.0991  1.0998  1.1006  1.1014

   1.1024  1.1036  1.1052  1.1073  1.1111  1.1193  1.1505  1.2977  1.3333
*  1.2034  1.2034  1.2034  1.2035  1.2037  1.2039  1.2041  1.2045  1.2048  1.2053  1.2058

*  1.2063  1.2069  1.2076  1.2092  1.2089  1.2097  1.2105  1.2113  1.2122  1.2132  1.2143

*  1.2157  1.2177  1.2206  1.2255  1.2346  1.2522  1.2860  1.3375  1.3333
   1.0616  1.0616  1.0616  1.0616  1.0617  1.0617  1.0619  1.0620  1.0622  1.0624  1.0626

   1.0629  1.0633  1.0636  1.0640  1.0645  1.0649  1.0654  1.0660  1.0666  1.0672  1.0678

   1.0686  1.0695  1.0707  1.0717  1.0740  1.0795  1.1033  1.2667  1.3333
*  1.1717  1.1717  1.1718  1.1719  1.1720  1.1721  1.1724  1.1726  1.1729  1.1733  1.1738

   1.1742  1.1748  1.1753  1.1760  1.1766  1.1774  1.1781  1.1789  1.1798  1.1807  1.1817

*  1.1829  1.1844  1.1969  1.1911  1.1995  1.2172  1.2545  1.3203  1.3333
   1.0309  1.0309  1.0309  1.0308  1.0308  1.0308  1.0308  1.0308  1.0309  1.0310  1.0311

   1.0312  1.0314  1.0316  1.0318  1.0320  1.0323  1.0326  1.0329  1.0333  1.0336  1.0340

   1.0345  1.0350  1.0356  1.0364  1.0375  1.0391  1.0576  1.2077  1.3333
*  1.1453  1.1453  1.1454  1.1454  1.1455  1.1456  1.1459  1.1460  1.1463  1.1466  1.1469

*  1.1473  1.1479  1.1483  1.1498  1.1494  1.1501  1.1508  1.1515  1.1523  1.1532  1.1540

*  1.1550  1.1561  1.1578  1.1610  1.1679  1.1847  1.2243  1.2963  1.3333
   1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000

   1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000

   1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000
*  1.1453  1.1453  1.1454  1.1454  1.1455  1.1456  1.1458  1.1460  1.1463  1.1466  1.1469

.  1.1473  1.1479  1.1483  1.1488  1.1494  1.1501  1.1508  1.1515  1.1523  1.1532  1.1540

*  1.1550  1.1561  1.1578  1.1610  1.1679  1.1847  1.2243  1.2963  1.3333
STOP
%EOD
```

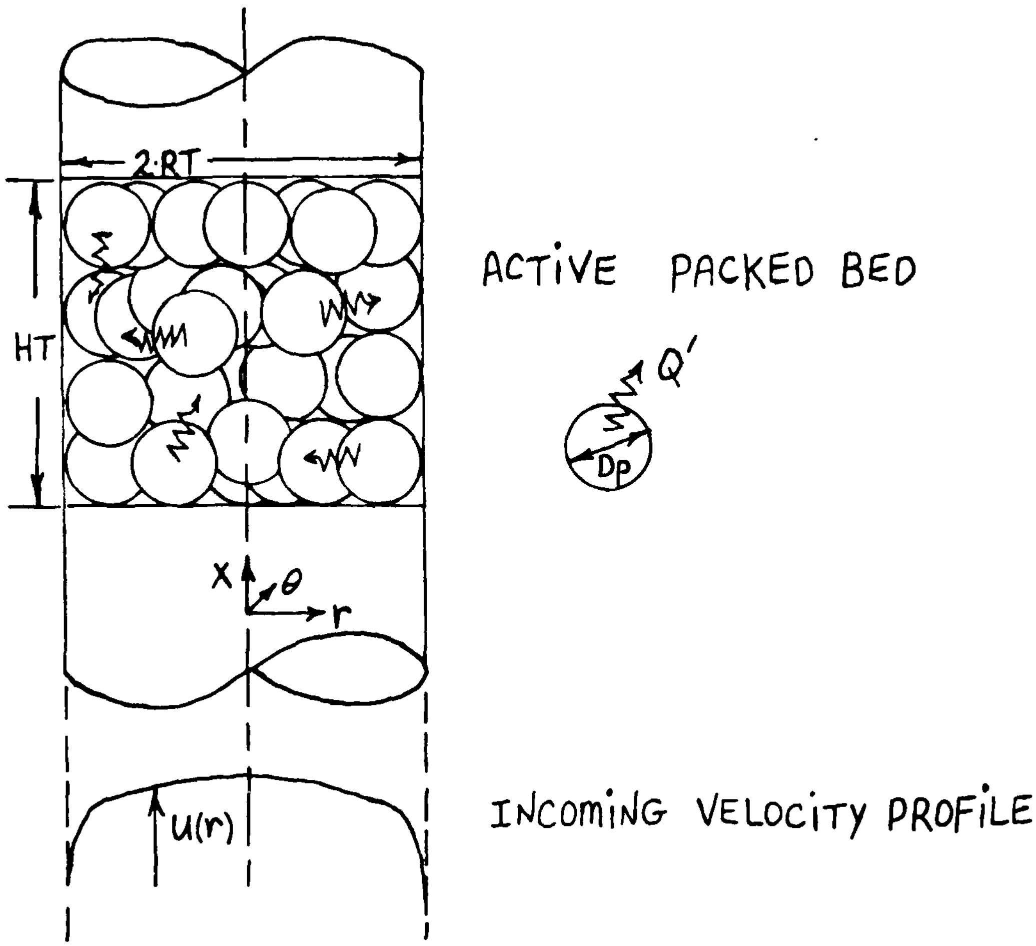
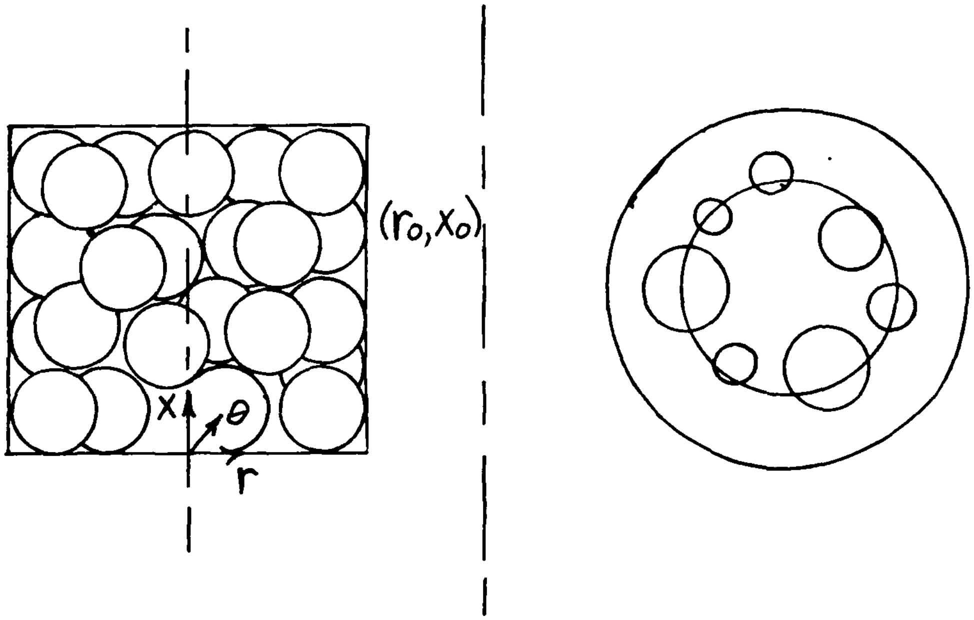


FIGURE 1. ILLUSTRATION OF ACTIVE PACKED BED



$$\epsilon(r_o, x_o) = \sum_i (r_o \cdot d\theta_i) / (2 \cdot \pi \cdot r_o)$$

$$= \sum_i d\theta_i / (2 \cdot \pi)$$

$\simeq 0.56$ FOR THE ABOVE EXAMPLE

FIGURE 2. ϵ AS A CONTINOUS FUNCTION OF X AND r.

$$
\left[\begin{array}{c|c}
\begin{matrix} x & x & & 0 & \\ x & x & x & & \\ & x & x & x & \\ & & \ddots & \ddots & \ddots \\ 0 & & x & x & x \\ & & & x & x \end{matrix} &
\begin{matrix} x & & & 0 & \\ & x & & & \\ & & x & & \\ & & & \ddots & \\ 0 & & & x & \\ & & & & x \end{matrix} \\
\hline
\begin{matrix} x & & & 0 & \\ & x & & & \\ & & x & & \\ & & & \ddots & \\ 0 & & & x & \\ & & & & x \end{matrix} &
\begin{matrix} x & x & & 0 & \\ x & x & x & & \\ & x & x & x & \\ & & \ddots & \ddots & \ddots \\ 0 & & x & x & x \\ & & & x & x \end{matrix}
\end{array}\right]
\cdot
\left[\begin{array}{c} T_{i2} \\ \vdots \\ T_{iN-1} \\ \hline \theta_{i2} \\ \vdots \\ \theta_{iN-1} \end{array}\right]
=
\left[\begin{array}{c} x \\ x \\ x \\ \vdots \\ x \\ x \\ \hline x \\ x \\ x \\ \vdots \\ x \\ x \end{array}\right]
$$

FIGURE 3. FORM OF MATRIX EQUATION

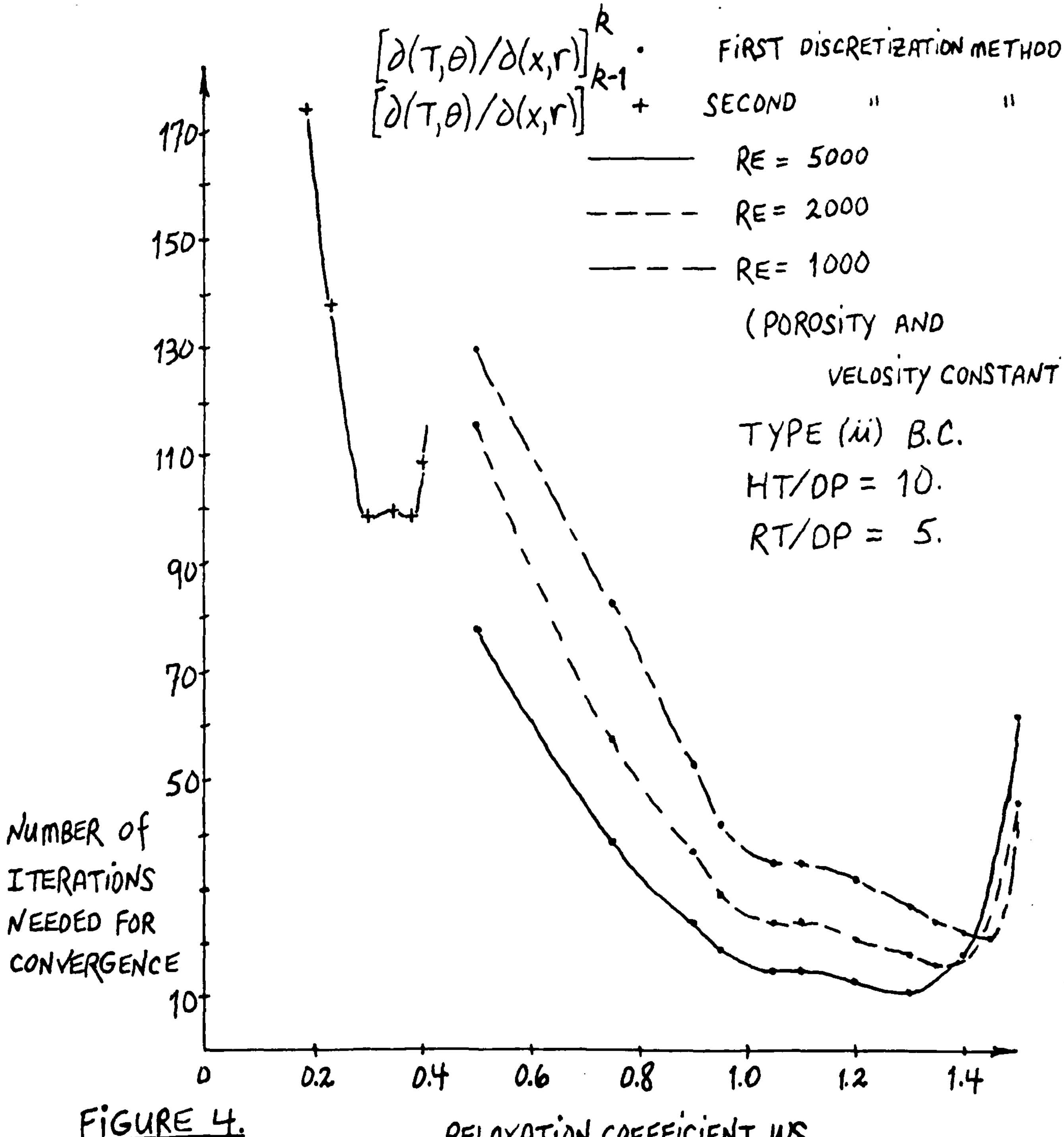


FIGURE 4.

OPTIMIZATION OF NUMERICAL PROCEEDURE

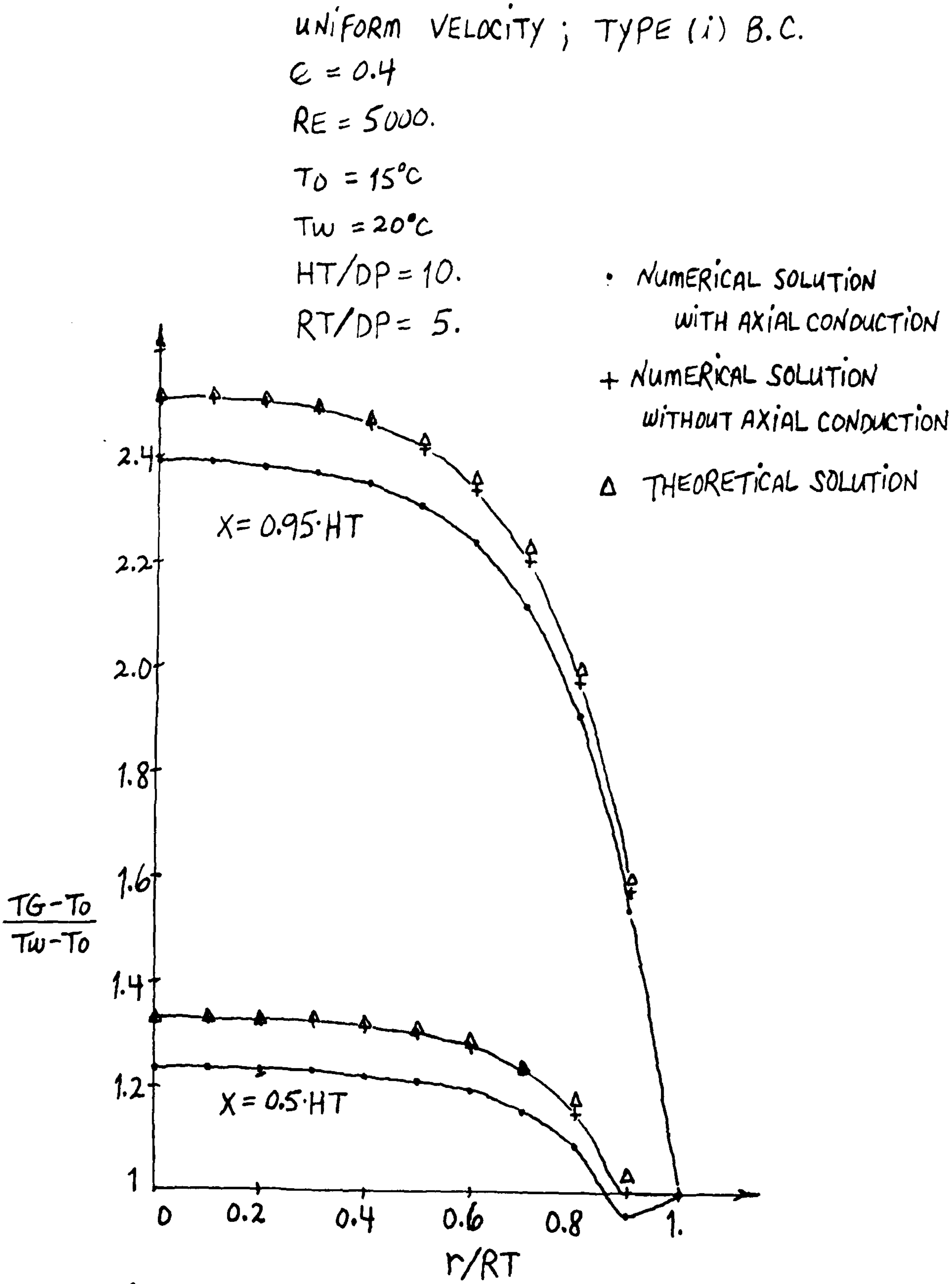


FIGURE 5. COMPARISON OF NUMERICAL PROCEDURES

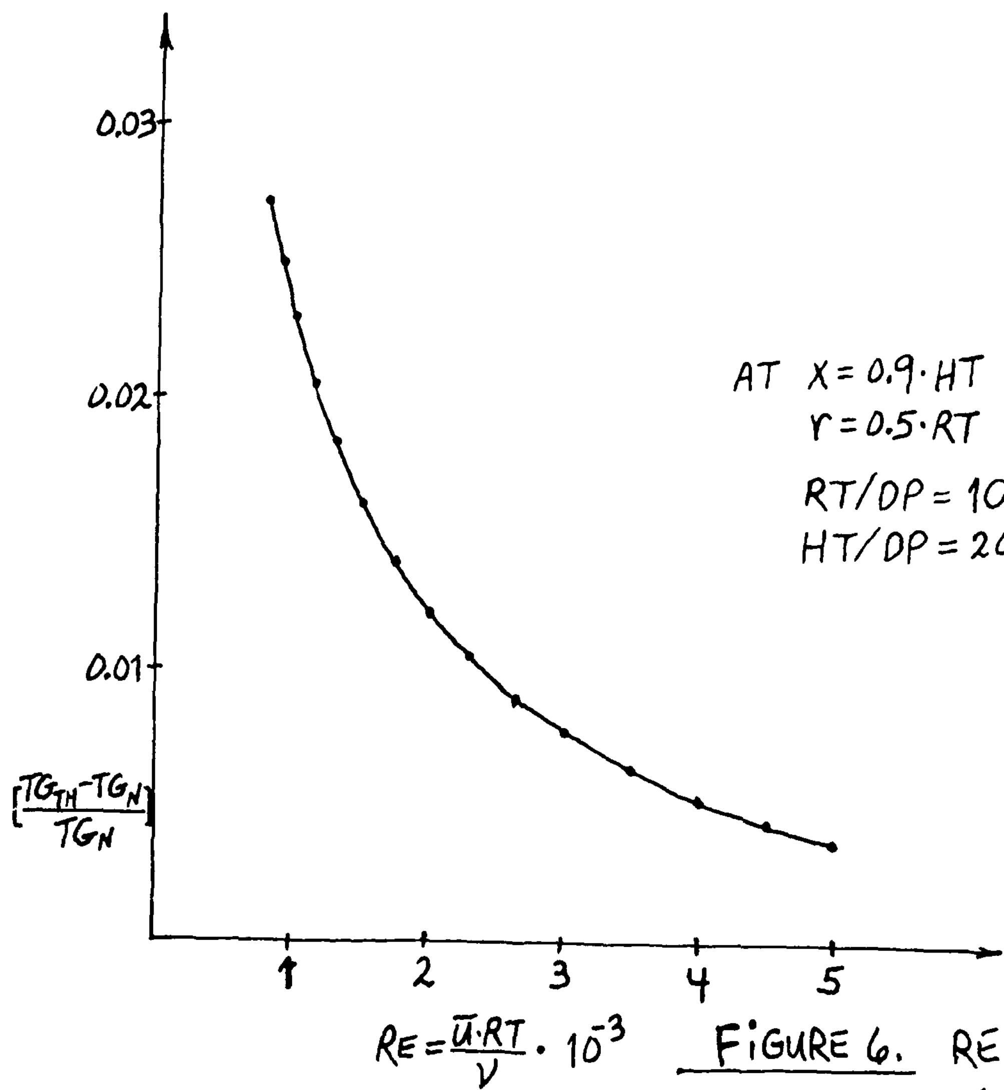


FIGURE 6. RE DEPENDANCE OF RELATIVE ERRO

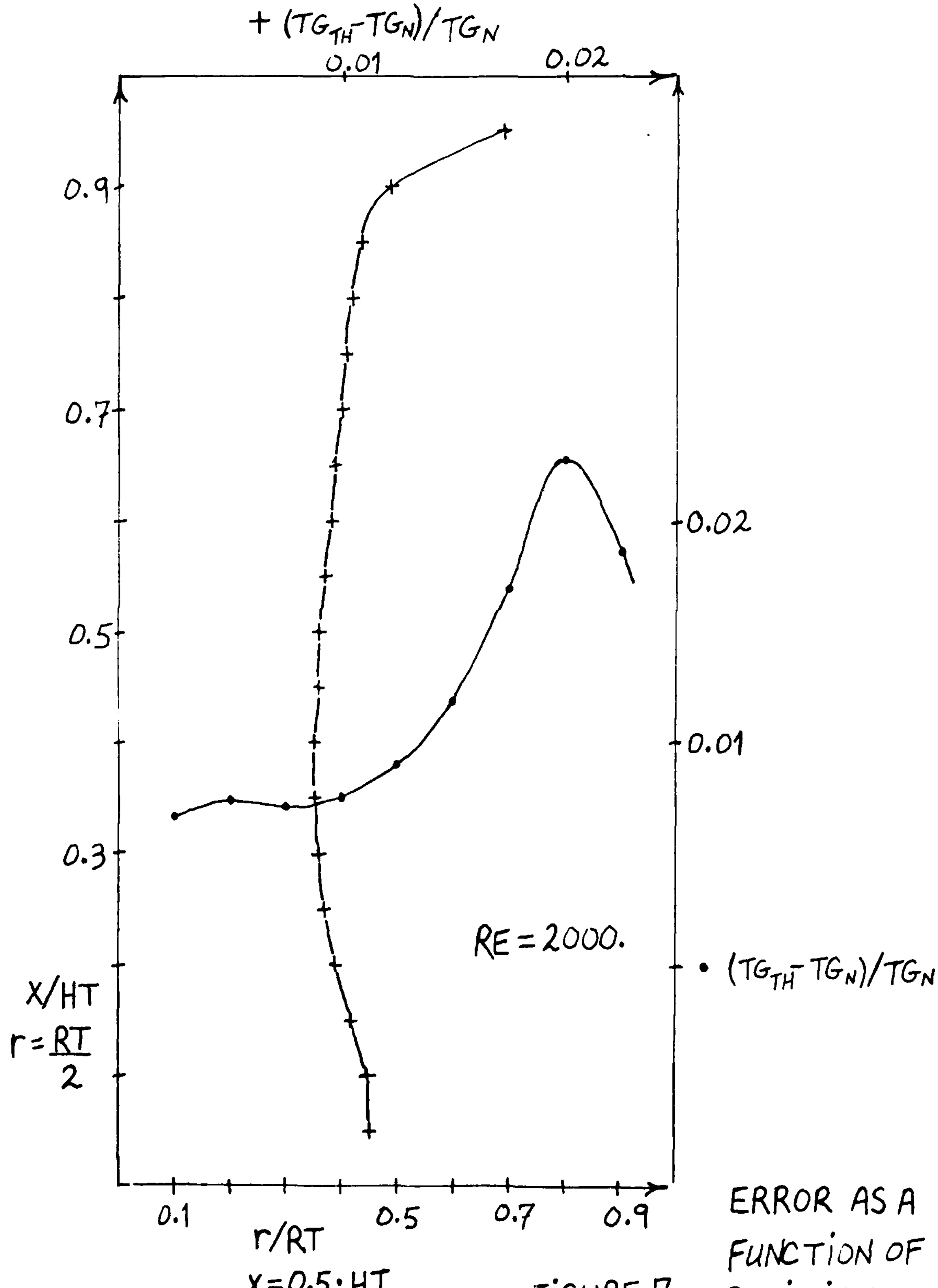
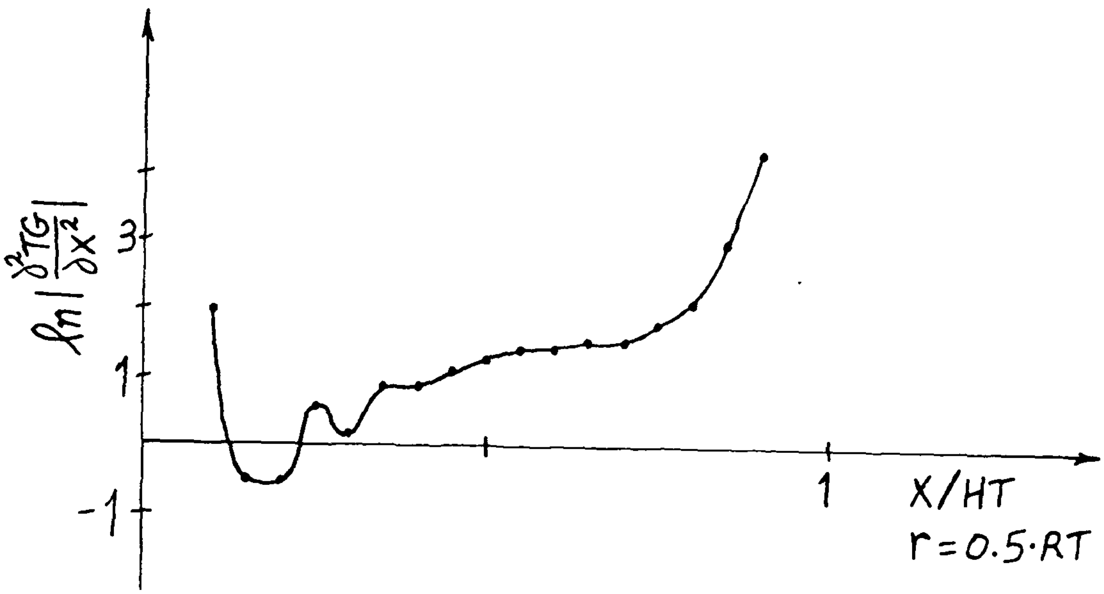


FIGURE 7 ERROR AS A FUNCTION OF POSITION



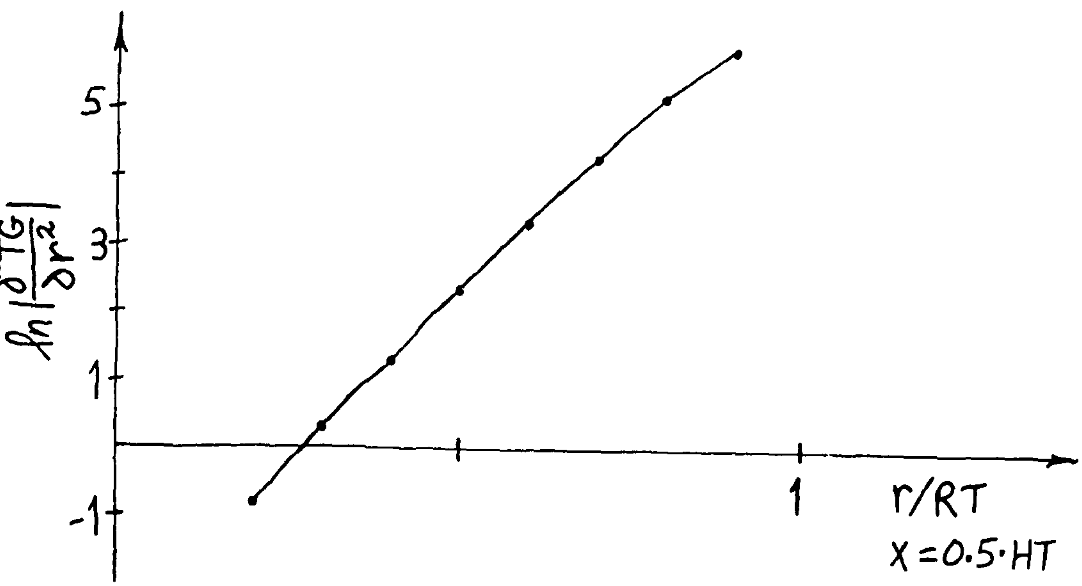


FIGURE 8. SECOND DERIVATIVES AS A FUNCTION OF POSITION

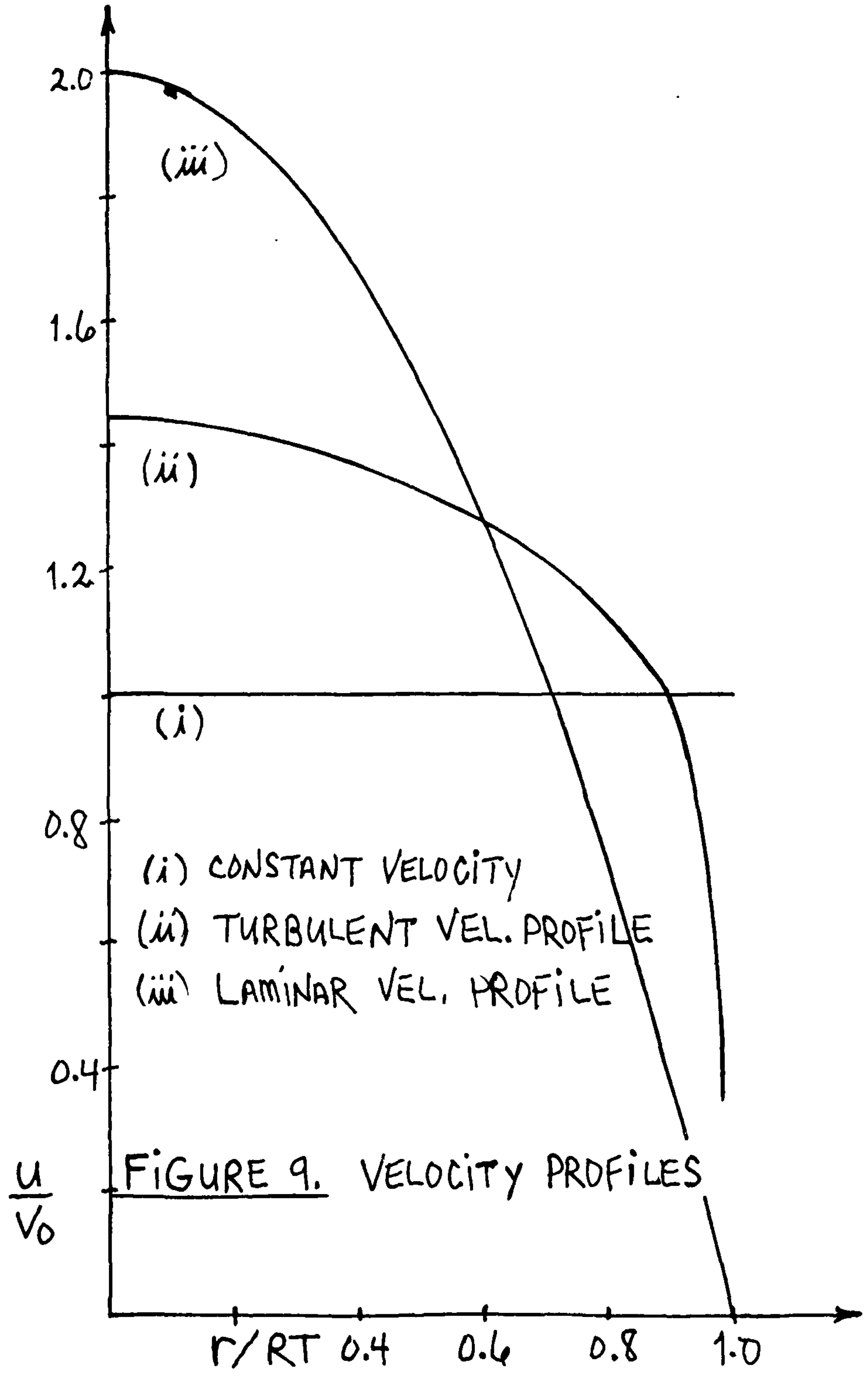
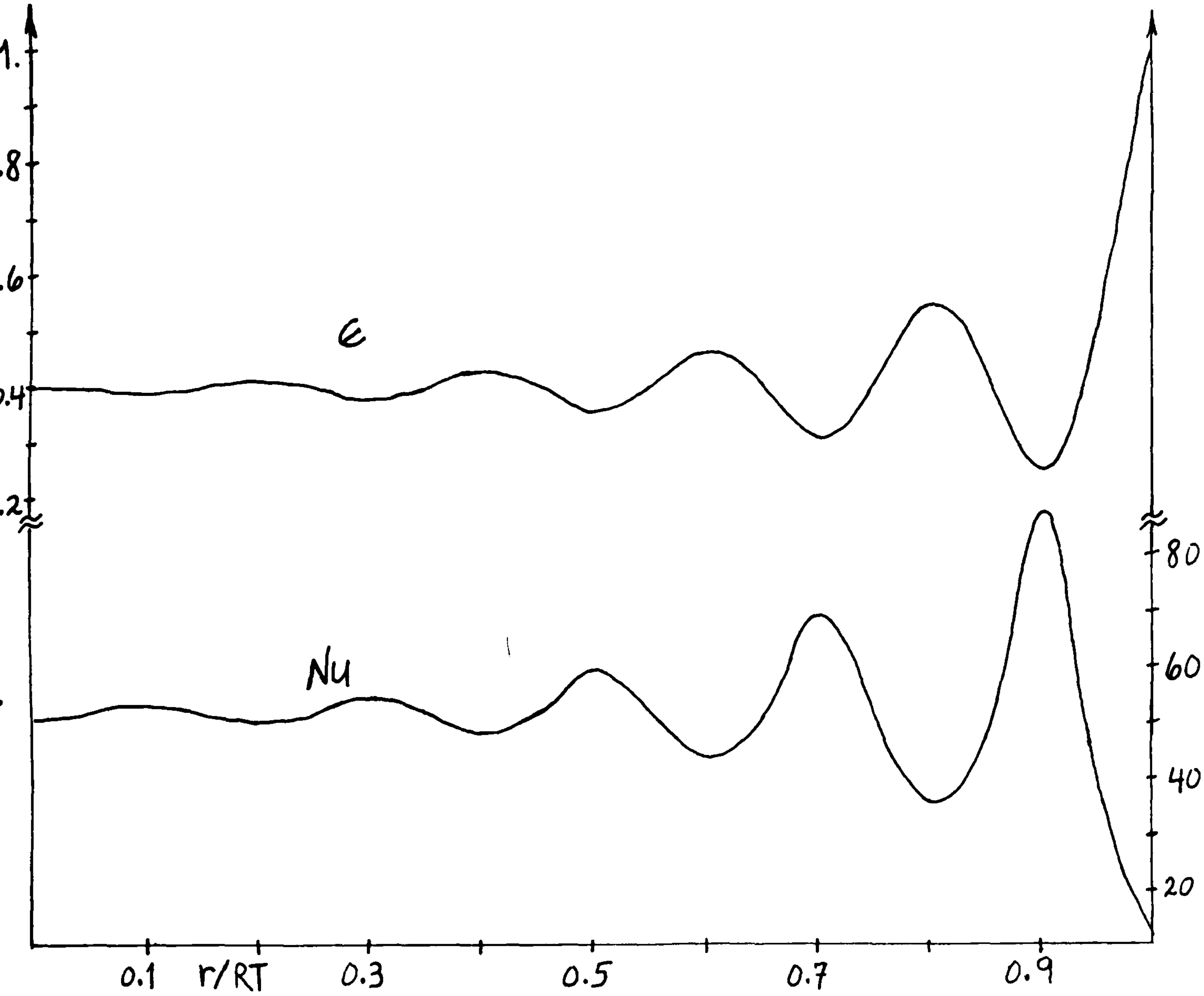


FIGURE 9. VELOCITY PROFILES



Nu(ε, RE, Pr)
RE = 5000.
Pr = 0.72

FIGURE 10.

POROSITY AND NUSSELT NUMBER DISTRIBUTIONS

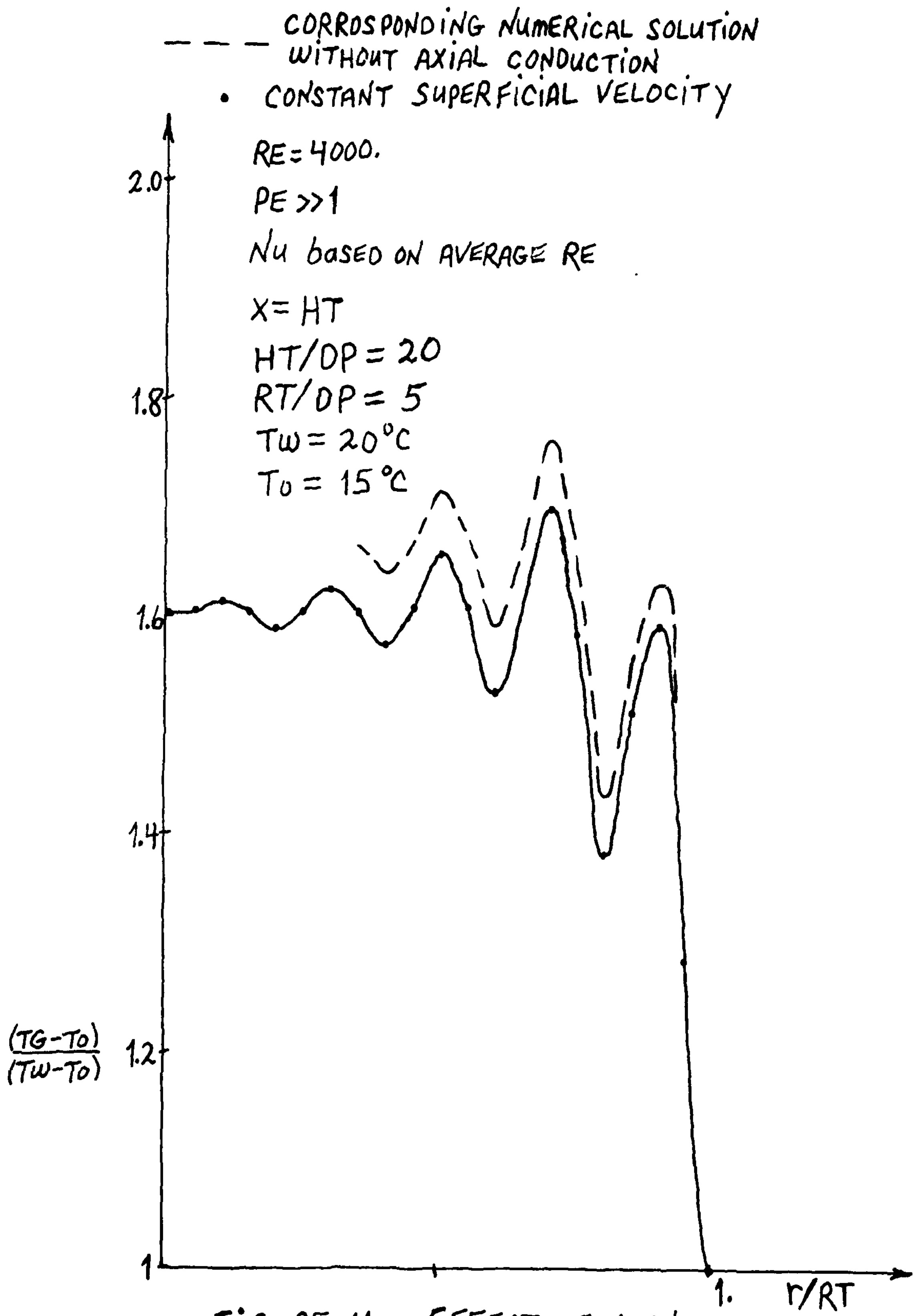


FIGURE 11. EFFECT OF ε ON TEMPERATURE PROFILE I

— — — CORROSPONDING NUMERICAL SOLUTION WITHOUT AXIAL CONDUCTION.

• TURBULENT SUPERFICIAL VELOCITY

RE = 4000.

PE ≫ 1

Nu BASED ON AVERAGE RE

X = HT

HT/DP = 20.

RT/DP = 5.

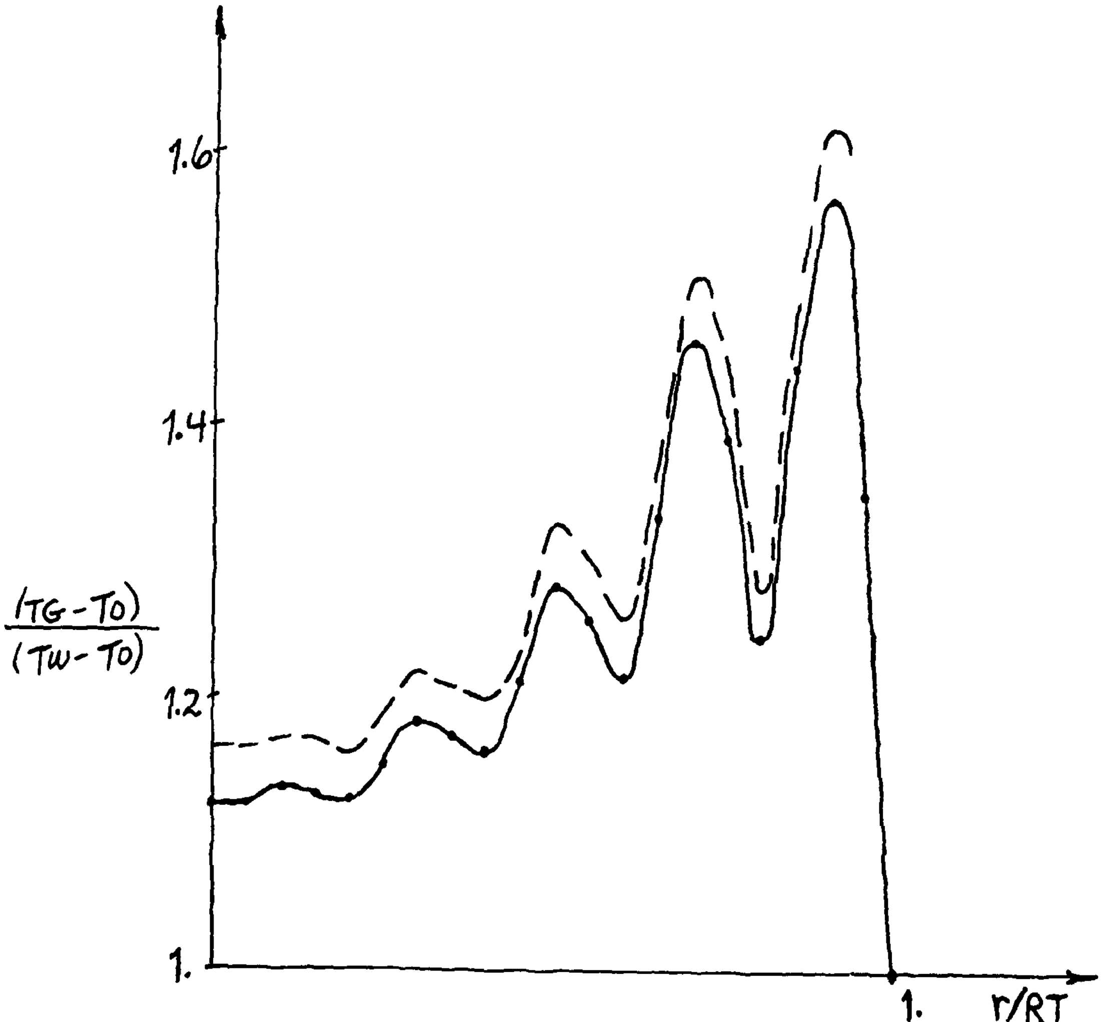


FIGURE 12. TEMPERATURE PROFILE II

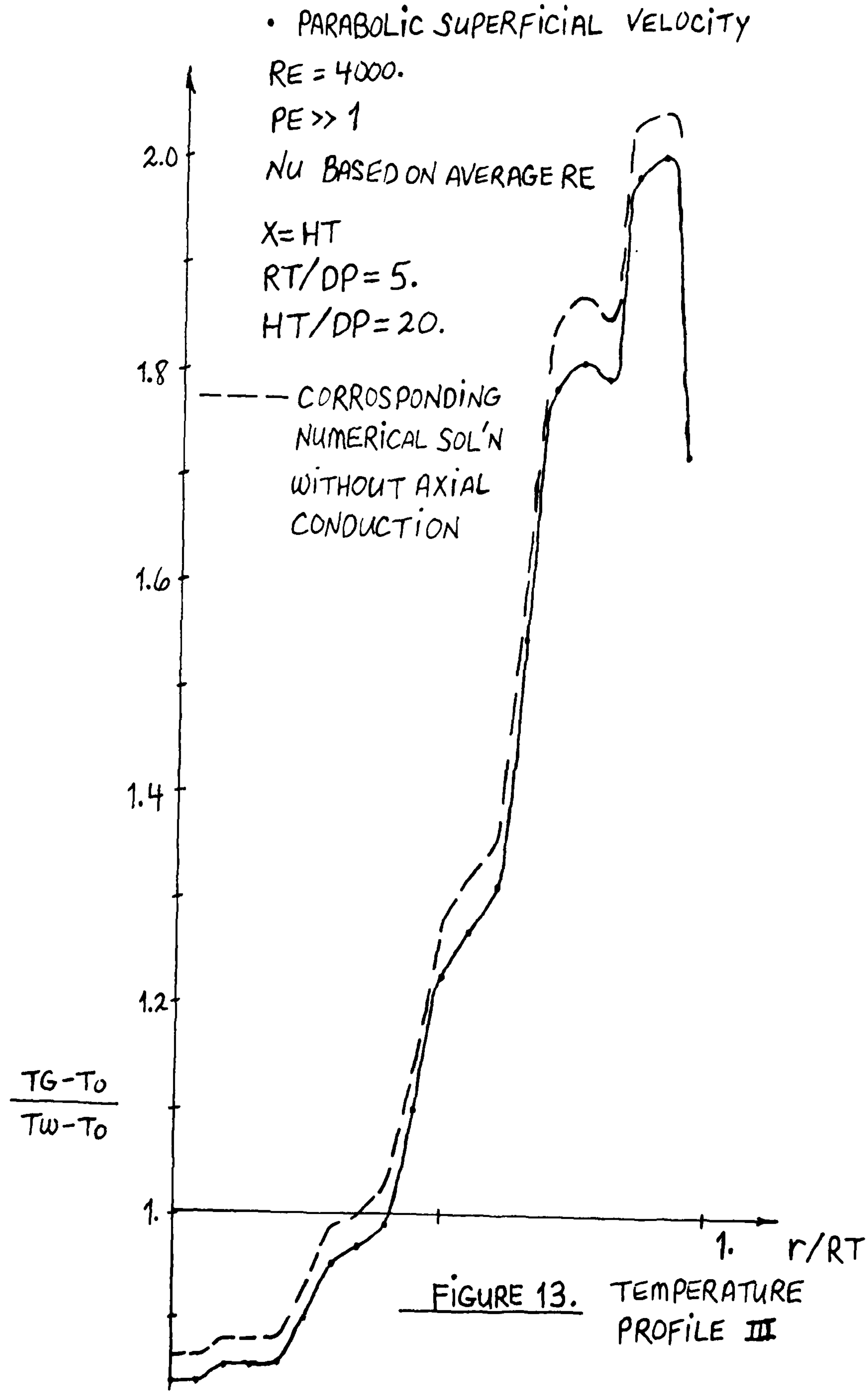


FIGURE 13. TEMPERATURE PROFILE III

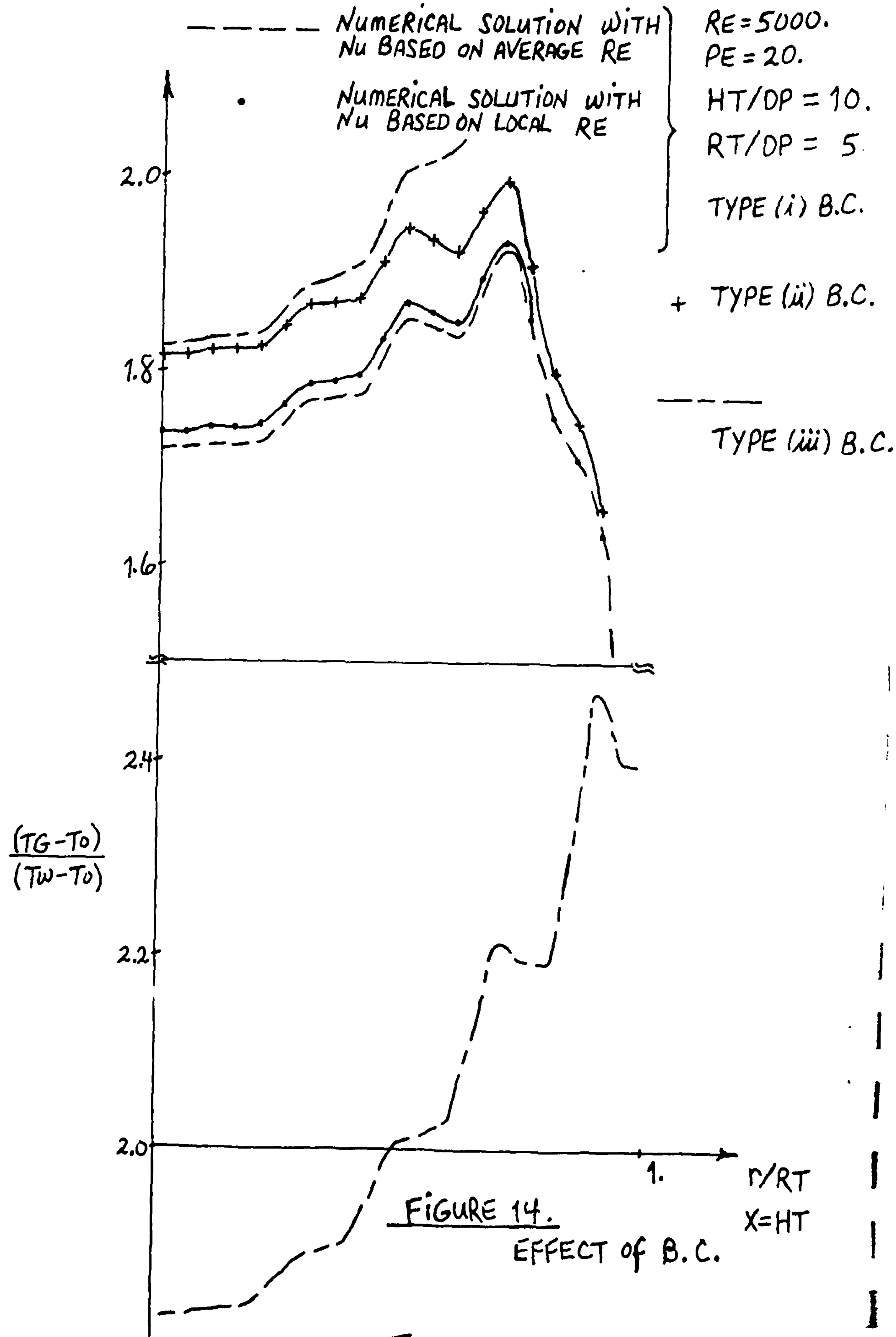


FIGURE 14.
EFFECT of B.C.

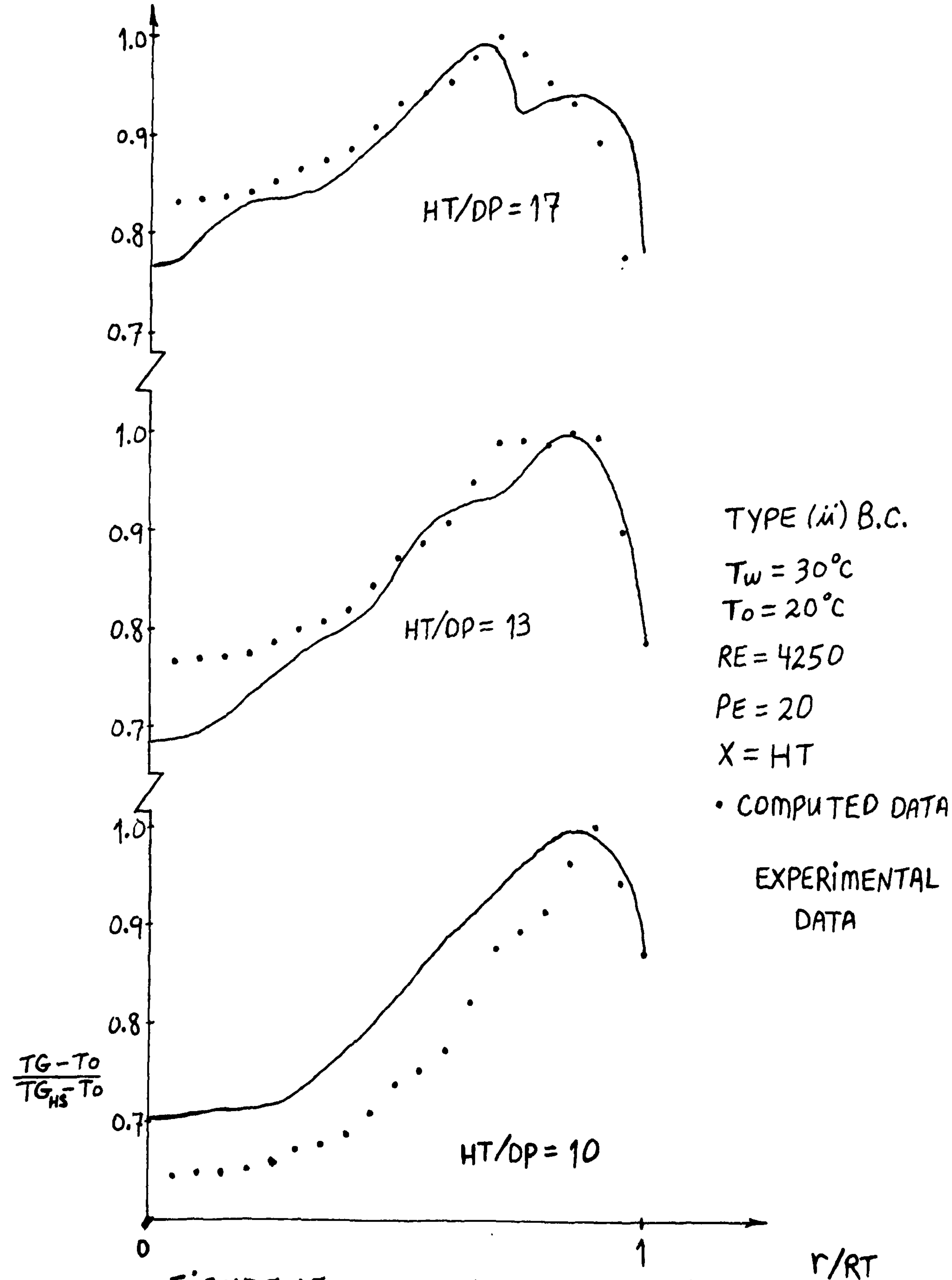


FIGURE 15. COMPARISON TO EXPERIMENTAL RESULTS

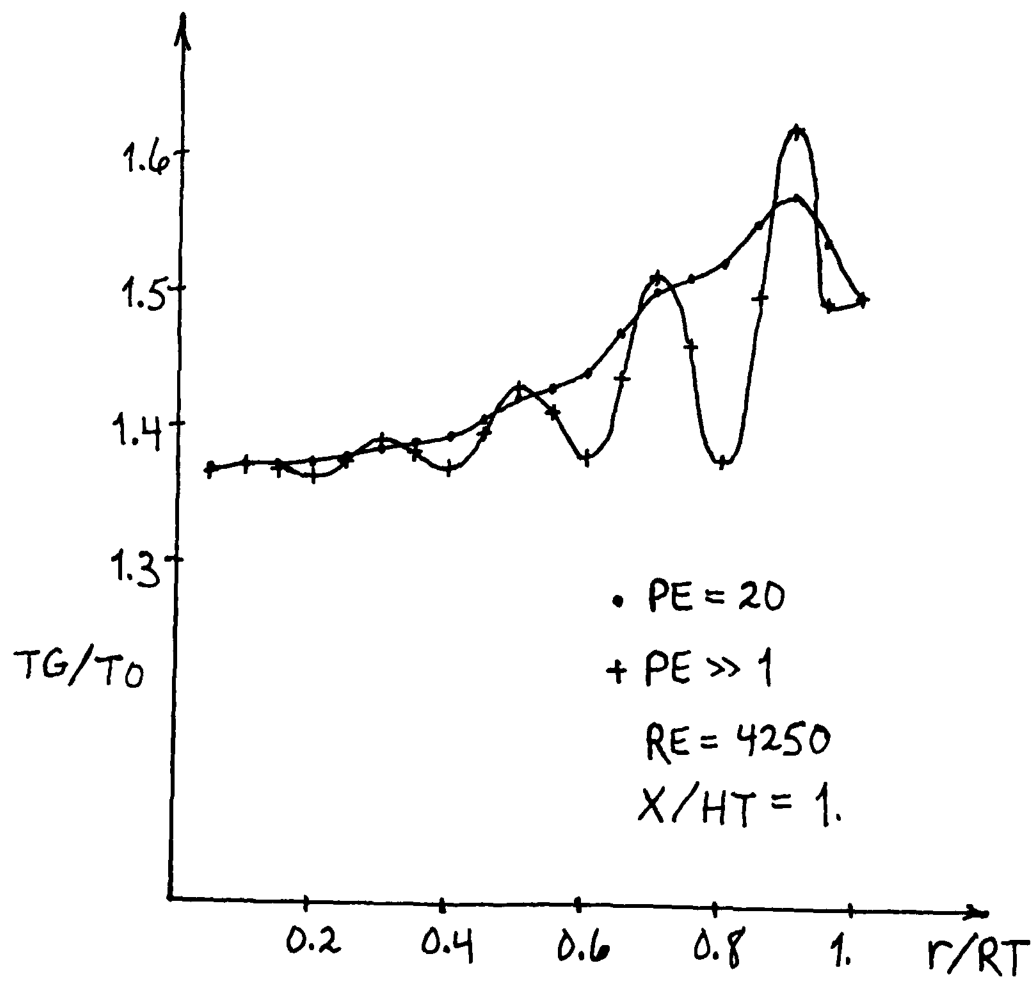
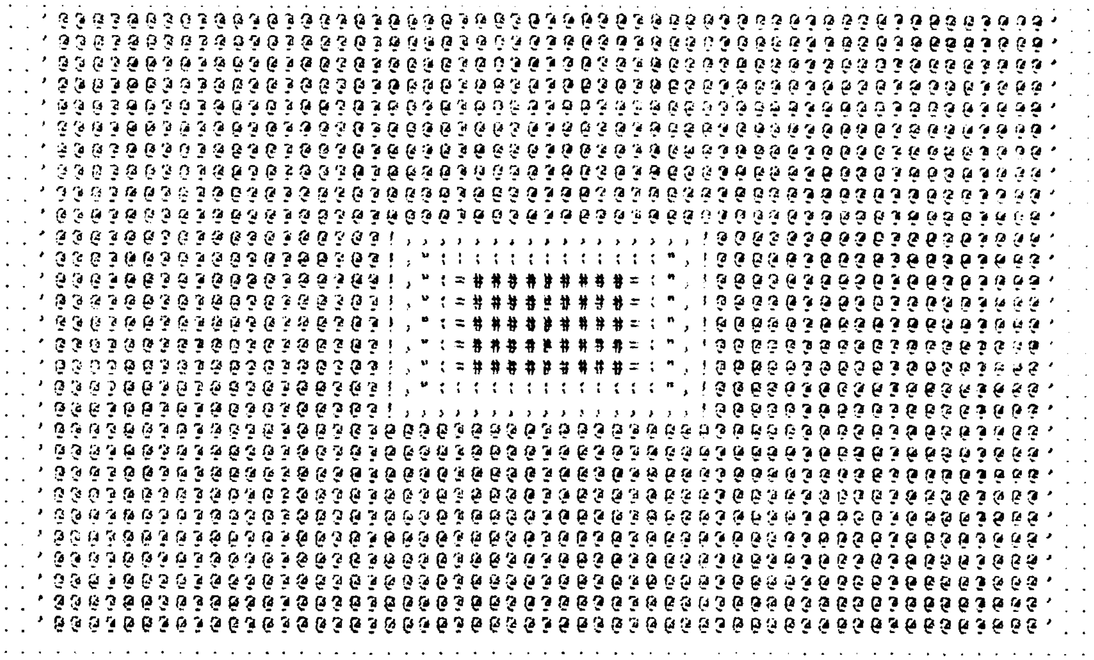


FIGURE 16. EFFECT OF PE

ISO-FRACTION DE VIDE



MINIMUM = 0.00000E-01 MAXIMUM = 4.00000E-01 CLASSES = 2.000

.	.LT.	2.000E-02	'	.LT.	2.200E-01
+	.LT.	4.000E-02	%	.LT.	2.400E-01
-	.LT.	6.000E-02	"	.LT.	2.600E-01
*	.LT.	8.000E-02	0	.LT.	2.800E-01
/	.LT.	1.000E-01		.LT.	3.000E-01
#	.LT.	1.200E-01	?	.LT.	3.200E-01
=	.LT.	1.400E-01	,	.LT.	3.400E-01
$	.LT.	1.600E-01	M	.LT.	3.600E-01
:	.LT.	1.800E-01	!	.LT.	3.800E-01
X	.LT.	2.000E-01	@	.LT.	4.000E-01

RE = 4000.
HT/DP = 20.
RT/DP = 10.

FIGURE 16.5

ε DISTRIBUTI
FOR BLOCKAGE

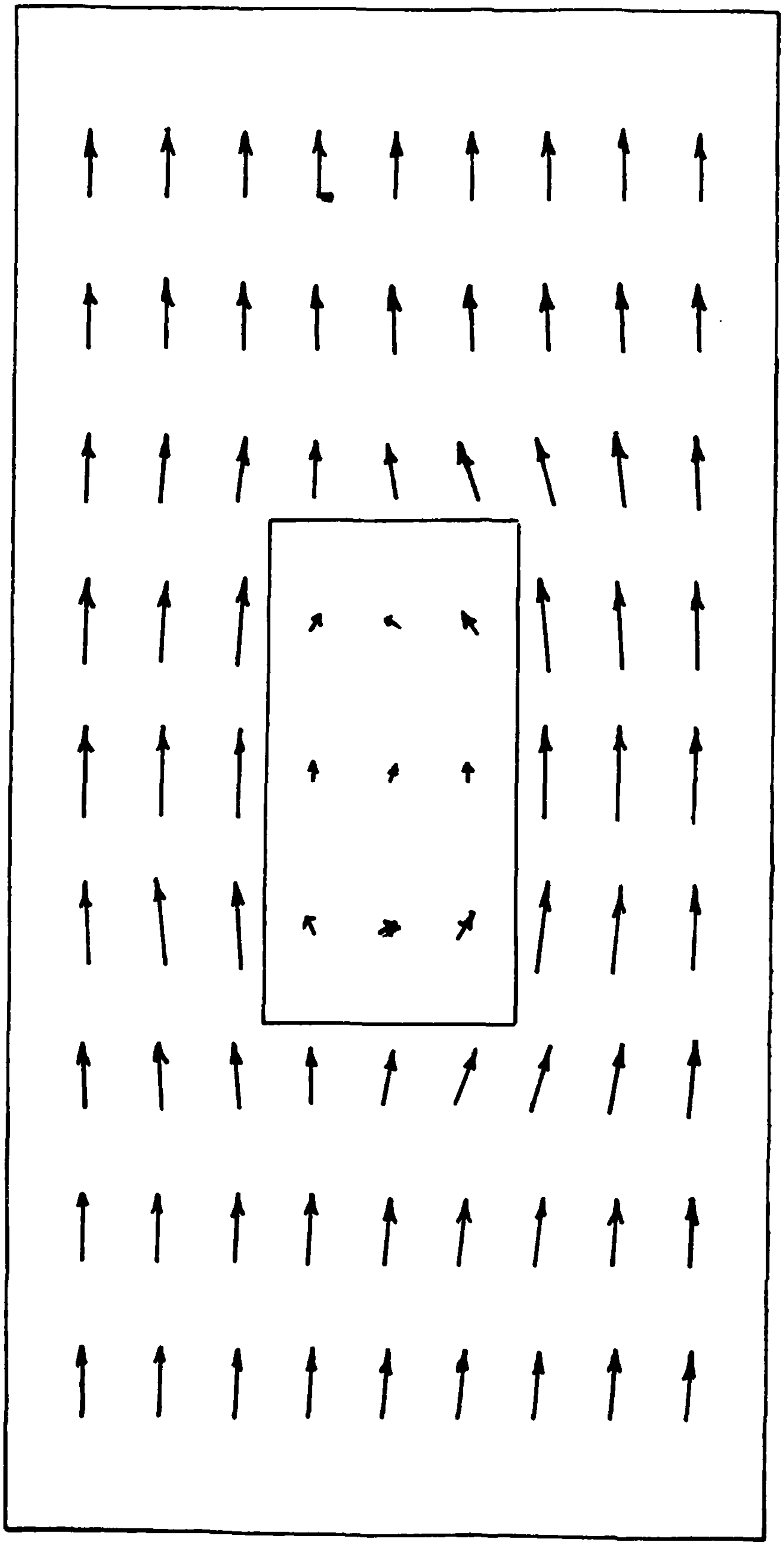


FIGURE 17. VELOCITY FIELD FOR BLOCKAGE

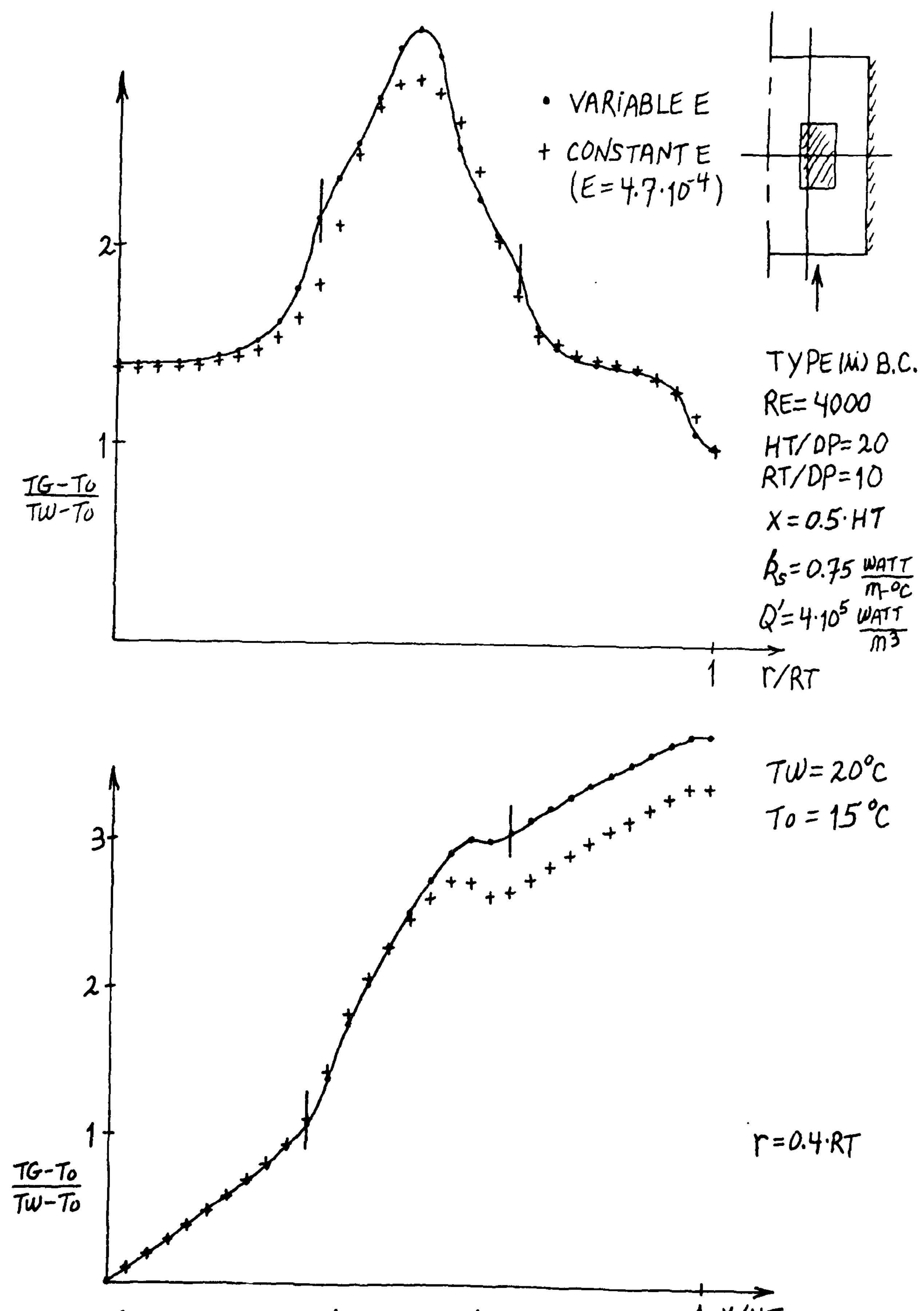


FIGURE 18. RADIAL AND AXIAL TEMP. PROFILES

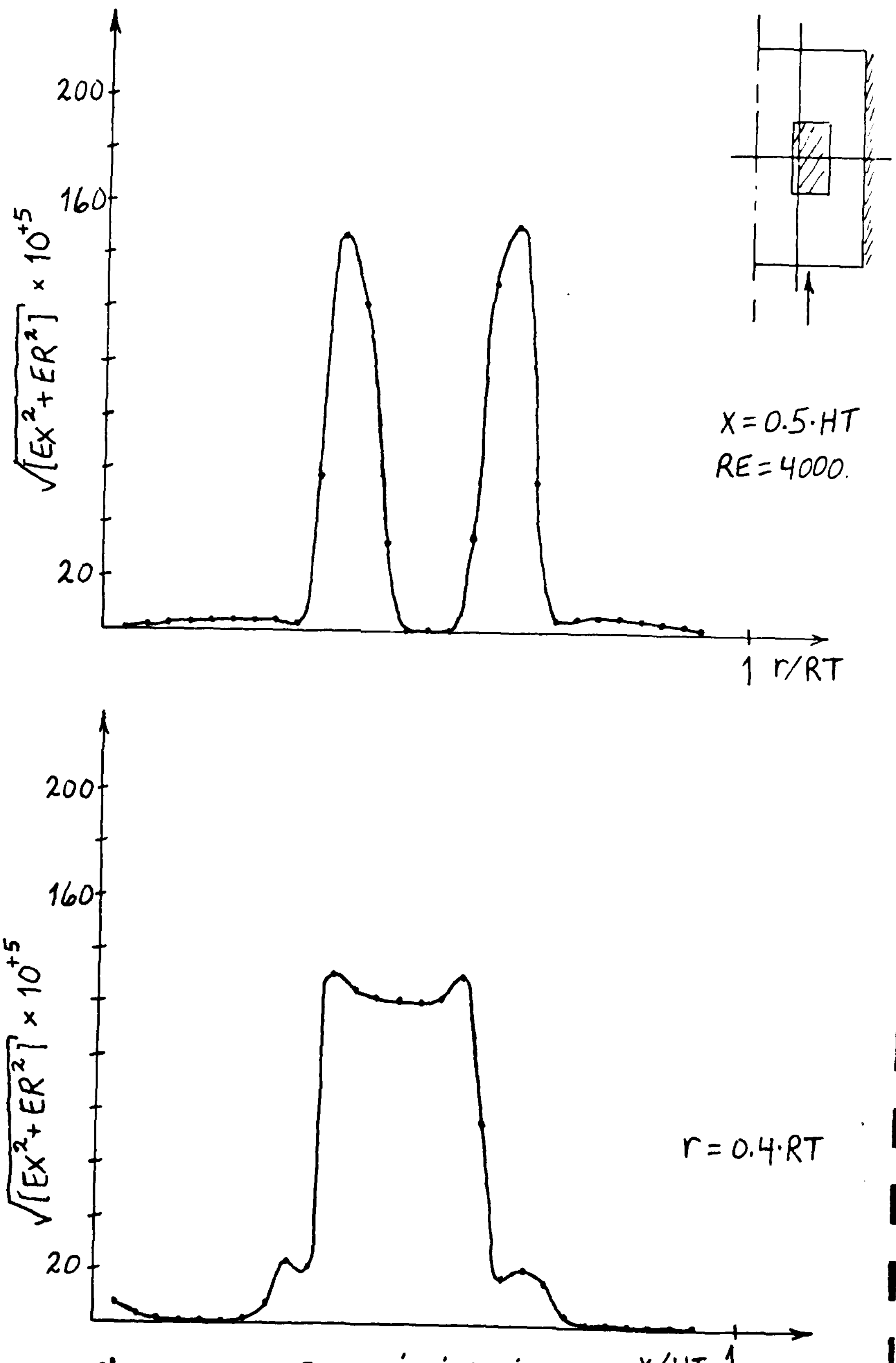


FIGURE 19. E VARIATIONS IN X AND r

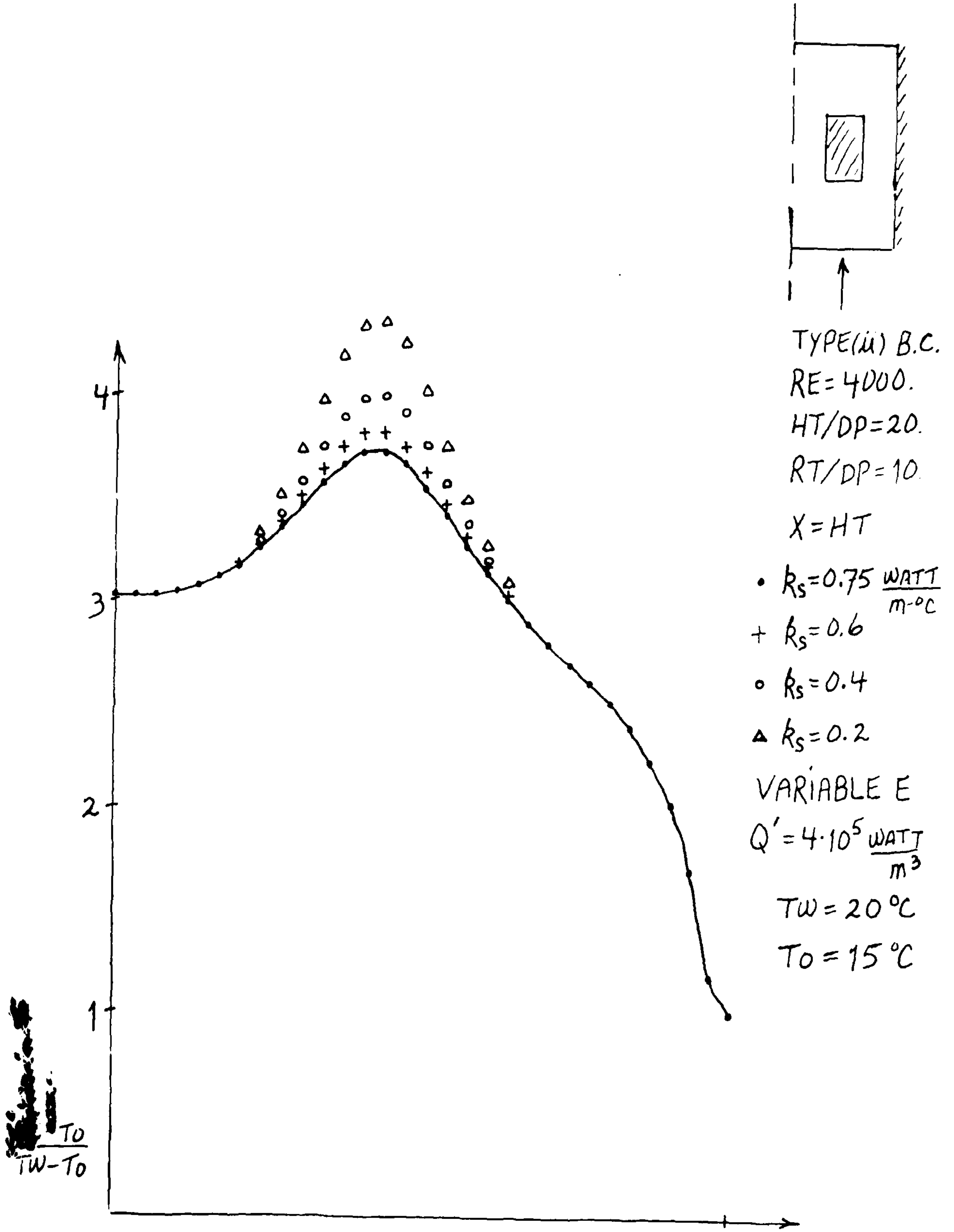


FIGURE 20. EFFECT of k_s^*

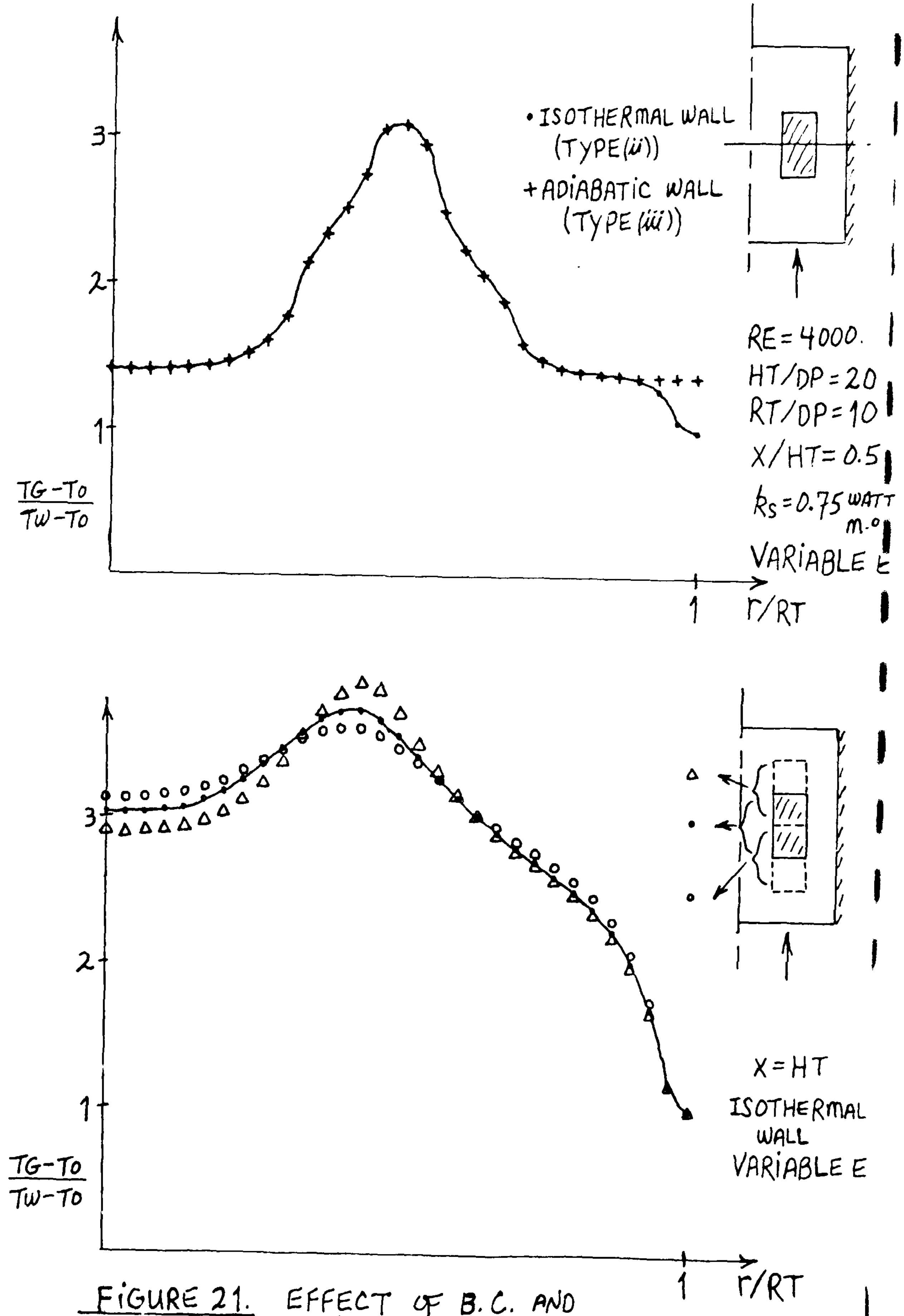


FIGURE 21. EFFECT OF B.C. AND POSITION OF BLOCKAGE.

END

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